PERFORMANCE OF CATHODIC PROTECTION FOR PIPE LINES

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ABSTRACT

Modeling of Cathodic Protection for Pipelines

The corrosion of metallic structures buried in soils or in contact with soils has long been a serious engineering and economic problem. All over the world millions of kilometers of gas, water, oil pipelines, communication cables, power cables as well as storage tanks, buildings foundations, and many other structures are buried in the soil, suffering from soil corrosion problems which affect mainly the external surfaces of these structures. In many countries pipelines are by far the most important means of hydrocarbon transportation. This applies to the transport of crude, finished products and natural gas.

It is an international problem with more structures and materials buried in the soil. The truly international scope of interest of this subject can be seen by the amount of literature and researches in this field. Attempts have been made to overcome this problem by the use of various types of techniques. The most common and applicable technique is cathodic protection.

In this research a carbon steel pipe of length 100 cm buried in a wooden box submerged by soil and impressed current cathodic protection system (ICCP). was applied using power supply and electrical closed circuit, several important factors affecting the pipe protection from corrosion has been studied, like Anode position (distance and depth), soil resistivity (wet and dry), condition the pipe (coated and un-coated), distribution of potential and currents along the pipe(cathode) and the amount of current required to achieve cathodic protection.

A correlation was achieved to simulate the ranges of parameters and factors affecting Impressed Current Cathodic Protection. Regression of this model to data and results yielded parameter values vary depending on the effect of the same factor.

Two equations were achieved in bare and coated pipe that explain the effect of many factors on the cathodic protection potential (-850mV) and the relation of each factors with others as shown below:

1. Bare carbon steel pipe.

ξ = 0.791+0.091 V +0.144 I -0.00188 D -0.00180 Dp -0.00537 m

2. Coated carbon steel pipe.

ξ = 0.467+0.742 V -1.675 I +0.00057 D -0.00067 Dp +0.2299 m

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Symbols	**Description**
ASTM	American Society for Testing and Materials
AC	Alternating current
BEM	Boundary Element Methode
BEASY	Boundary Element Analysis System
CSE	Copper/Copper Sulfate Electrode
CP	Chathodic Protection
DC	Direct Current
EMF	Electro Motive series
FEM	Finite Element Method
ICCP	Impressed Current Cathodic Protection
MMO	Mixed Metal Oxide
mdd	Milligram per square decimeter per day
mpy	Milli-inch penetration per year
NACE	National Association for Catering and Events
SCC	Stress Corrosion Cracking
SACP	Sacrificial Anode Cathodic Protection
SCE	Saturated Calomel Electrode
RE	Refrence Electrode

Variable Notations

Symbols	**Description**	**Unit**
CP_{power}	Cathodic protection power	Watts
CR	Corrosion Rate	mdd and mpy
F	Faraday's constant (96487)	C/mole
E	electrochemical potential	mV
E°	equilibrium potential	mV
E_a	Anodic potential	mV
E_c	Cathodic potential	mV
E_{corr}	Corrosion potential	mV
E_p	Protection potential	mV
Si	stoichiometric coefficient of species i	[-]
I	Total current required	mA
i_a	Anodic Current density	mA/cm^2
ic	Cathodic Current density	mA/cm^2
i_{cp}	cathodic protection current density	mA/cm^2
iL	Limiting Current density	mA/cm^2
κ	Soil conductivity	mS/m
ρ	environment resistivity	Ω. Cm
R	Resistance	Ω
ΔV	difference in voltage versus SCE	V
D	Distance of anode from cathode	cm

Dp	Depth of anode from cathode	cm
m	Environment (soil), moisture	%
ξ	Cathodic protection potential (-0.85 to -1.1)	V

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Chapter One

Introduction

1.1 Historical Background

Corrosion can pose serious problems to the safe and economic operation of a wide variety of industrial installations. However, in order to understand a corrosion problem or situation, it is very important to be able to recognize the type of problem one is dealing with and to study the possible means for corrosion prevention. Cathodic protection (CP) method is the most important in order to prevent underground corrosion. Corrosion will cost the US economy over $1 trillion in 2013. The total annual cost in the U.S. is expected to rise above $1 trillion in the middle of 2013, illustrating the broad and expensive challenge that corrosion presents to equipment and materials. The most commonly quoted figure for corrosion costs is $276B in 1998, which was reported in the NACE Corrosion Costs Study [1].

The first practical use of cathodic protection is generally credited to Sir Humphrey Davy in the 1820's. Davy advice was sought by the Royal Navy in investigating the corrosion of copper sheeting used for cladding the hulls of naval vessels. Davy found that he could preserve copper in sea water by the attachment of small quantities of iron or zinc; the copper became, cathodically protected.

The most rapid development of cathodic-protection systems was made in the United States of America to meet the requirements of the rapidly expanding oil and natural gas industry which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission. For that purpose the method was well established in the United States in 1945. In the United

Kingdom, where low-pressure thicker-walled cast-iron pipes were extensively used, very little cathodic protection was applied until the early 1950’s. The increasing use of cathodic protection has arisen from the success of the method used from 1952 onwards to protect about 1000 miles of wartime fuel-line network that had been laid between 1940 and 1944. The method is now well established. Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte. In practice its main use is to protect steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion. Structures commonly protected are the exterior surfaces of pipelines, ships’ hulls, jetties, foundation piling, and steel sheet-piling and offshore platforms. Cathodic protection is also used on the interior surfaces of water-storage tanks and water-circulating systems. However, since an external anode will seldom spread the protection for a distance of more than two or three pipe-diameters, the method is not suitable for the protection of small-bore pipe work. Cathodic protection has also been applied to steel embedded in concrete, to copper-based alloys in water systems, and, exceptionally, to lead-sheathed cables and to aluminum alloys, where cathodic potentials have to be very carefully controlled [2].

1.2 Objectives of the Study

Study of factors affecting the cathodic protection of pipelines buried under the soil using the method of the Impressed Current Cathodic Protection (ICCP) These factors include Anode position (distance and depth), soil resistivity (wet and dry), condition the pipe (coated and un-coated), distribution of potential and currents along the pipe (cathode), the amount of current required to achieve cathodic protection and make a mathematical model Simulate the ranges of all parameters and factors above and the influence of it at the environmental situation in Iraq.

Chapter Two

Literature Review

2.1 General Review

In Iraq over the last several years there has been much controversy in industry over corrosion control strategies for pipeline used in different industries. Much of this stems from the application of corrosion control that were developed primarily to address protection oil and gas energy pipelines where complete cathodic protection is mandated and corrosion is not acceptable. Typically for pipelines, some corrosion is tolerable and these pipelines are typically not regulated. Iraq has the world's second largest proven oil reserves. Iraq's oilfields are divided into two main production areas the southern fields and the northern fields. Figure (2-1) shows the map of these fields and the network of pipelines [3].

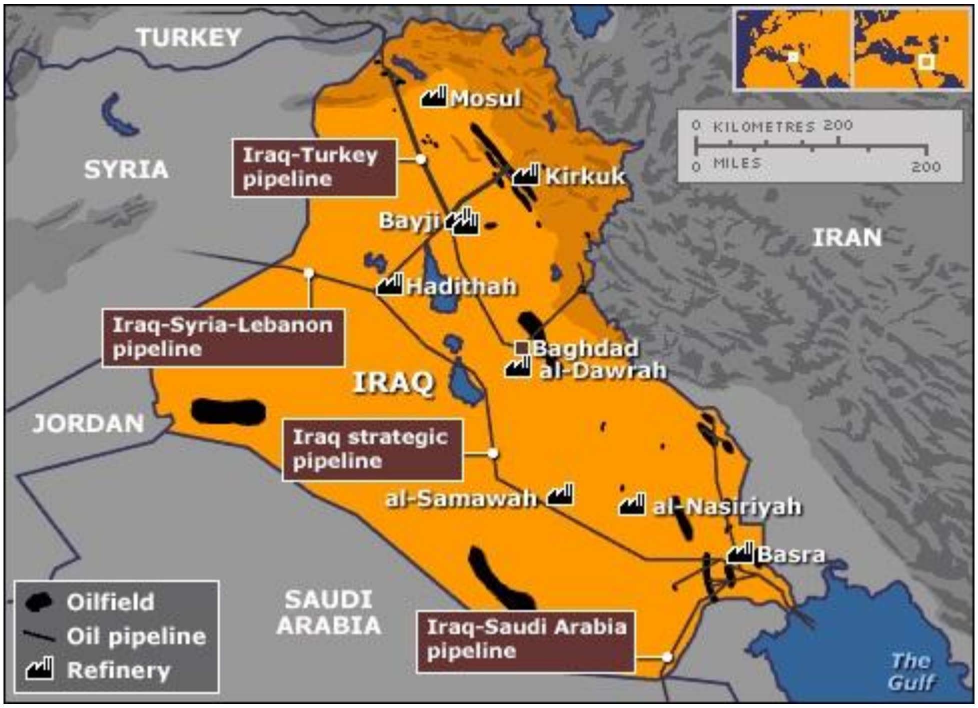

Figure (2-1) Crude oil field and pipe lines [3]

2.2 Corrosion

Corrosion can be defined as the deterioration of material by reaction to its environment. The corrosion occurs because of the natural tendency for most metals to return to their natural state; e.g., iron in the presence of moist air will revert to its natural state, iron oxide. Metals can be corroded by the direct reaction of the metal to a chemical; e.g., zinc will react with dilute sulfuric acid, and magnesium will react with alcohols [4].

Corrosion takes place in response to the tendency to reduce the overall free energy of a system. For example, when metal is in a dilute aerated neutral electrolyte atmosphere, moisture film, which contain oxygen and water, usually cover the metal surface. Some atoms in the metal surface tend to give out electrons and become ions in the moisture layer. In this way, they are in a lower energy state in solution than when they are in the lattice of the solid metal. At the same time the metal surface builds up a huge excess negative charge. These electrons move out from the metal and attach themselves to protons (H^+ ions) and molecules oxygen (O_2). The process repeats itself on various parts of the surface, and then the metal dissolves away as ions. [5]

The primary constituent of pipeline-grade steels is iron. Therefore the overall corrosion reaction can be written in terms of dissolution of iron, e.g.

$$2Fe+O_2+2H_2O \rightarrow 2Fe(OH)_2 \qquad E^\circ = 0.85V \qquad \ldots (2\text{-}1)$$

Reaction (2-1) can be considered as the result of two half-cell reactions. One is

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad E^\circ = 0.45V \qquad \ldots (2\text{-}2)$$

This is an oxidation reaction with an increase of oxidation state for iron from 0 to 2^+. It is called an anodic reaction. The other is:

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \qquad E^\circ = 0.4V \qquad \text{… (2-3)}$$

This reaction is a reduction reaction with a decrease of oxidation state for O_2 to OH^-. It is defined to be a cathodic reaction. The change in free energy associated with reaction (2-1) can be expressed in terms of a cell potential as:

$$\Delta G = -nF\,\Delta E \qquad \text{… (2-4)}$$

Where n is the number of electrons exchanged in the reaction, F is Faraday's constant, 96487 coulombs/equivalent, and E is the electrochemical potential. [6] According to the Nernst equation, obtained by neglecting both activity coefficients and liquid-junction potential:

$$\Delta E = \Delta E^\circ - \frac{RT}{nF}\ln\left(\Pi\left(a_i^{si}\right)\right) = \Delta E^\circ - \frac{RT}{nF}\ln\left(\Pi\left(c_i^{si}\right)\right) \qquad \text{… (2-5)}$$

Where E° is the equilibrium potential, and a_i is the activity of the species *i*, si is the stoichiometric coefficient of species i, and ci is the concentration of the species i. For reaction (2-2), the potential in Nernst equation form is:

$$E_a = E^\circ_{Fe^{2+}/Fe} - \frac{RT}{2F}\ln\left([Fe^{2+}]\right) \qquad \text{… (2-6)}$$

Likewise, for reaction (2-3), the potential in Nernst equation form is:

$$E_c = E^{\circ}_{\frac{O_2}{OH^-}} - \frac{RT}{4F}\ln\left(\frac{[OH^-]^4}{P_{O_2}}\right) \qquad \ldots (2\text{-}7)$$

Where (a) mean anodic reaction and (c) refers to the cathodic reaction. To the whole reaction, where na = 2 and nc = 4,

$$\Delta G = 2\Delta G_a + \Delta G_c = -2n_aFE_a - n_cFE_c = -4F(E_a + E_c) \qquad \ldots (2\text{-}8)$$

For the two half-cell reactions, E_a and E_c are positive. Hence, the free energy of the overall reaction must be negative, which means the corrosion reaction occurs spontaneously. [7]

2.3 Common Forms of Corrosion Encountered on Buried Metallic Pipelines

The commonly observed forms of corrosion of metallic pipelines embedded in backfill materials. Some corrosion forms such as the stray current corrosion which is the rate and occurrence of these corrosion forms are not related to the type of backfill soil but in this section will mention for the stray current corrosion as example and because it is important to understand the corrosion [8].

2.3.1 Uniform Corrosion of Metallic Pipe

Uniform corrosion or general corrosion is as shown in Figure (2-2) uniform corrosion process exhibiting uniform thinning that proceeds without appreciable localized attack. It is the most common form of corrosion and may appear initially as a single penetration, but with thorough examination of the cross section it becomes apparent that the base material has uniformly thinned. This is characterized by an even distribution of corrosion that leaves the surface clean or coated with corrosion products.

This even distribution is due to the movement of the anodic and cathodic sites on the metal’s surface. With uniform attack, fouling of the metal is usually a bigger problem than failure because for uniform corrosion to occur, the metallurgical composition of the metal must be uniform and the exposure conditions must be homogeneous over the whole surface [9].

Figure (2-2) Uniform Corrosion [10]

2.3.2 Pitting Corrosion

Pitting corrosion is a localized form of corrosion by which cavities, or holes, are produced in the material. Pitting is considered to be more dangerous than uniform corrosion damage because it is more difficult to detect, predict, and design against. Corrosion products often cover the pits. A small, narrow pit with minimal overall metal loss can lead to the failure of an entire engineering system [11].

Figure (2-3) shows the details of a pipe wall at an anode undergoing pitting corrosion [*12*].

2.3.3 Corrosion Due to Dissimilar Metals

It occurs when dissimilar metals are in contact in the presence of an electrolyte, such as water (moisture) containing very small amounts of acid .The dissimilar metals set up a galvanic action that result in the deterioration of one of them.

The following is a list of the more common commercial metals, sequenced according to what is known as the Galvanic Series:

1 .Aluminum
2 .Zinc
3 .Steel
4 .Iron
5 .Nickel
6 .Stainless Steel 400 series
7 .Tin
8 .Lead
9 .Brass
10 .Copper
11 .Bronze
12 .StainlessSteel300 series

When any two metals in this list are in contact, with an electrolytic present, the one with the lower number is corroded. The galvanic action increases as they are farther apart in the Galvanic Series. It is not always metals true that there is greater corrosion the further down the scale one goes. In certain cases one metal immediately following another may be very corrosive. Figure (2-4) shows Corrosion due to dissimilar metals shows corrosion due to dissimilar metals examples. One of the most important facts that an architect should know about a metal or an alloy is its reaction with other metals or alloys with which it may be in contact [9].

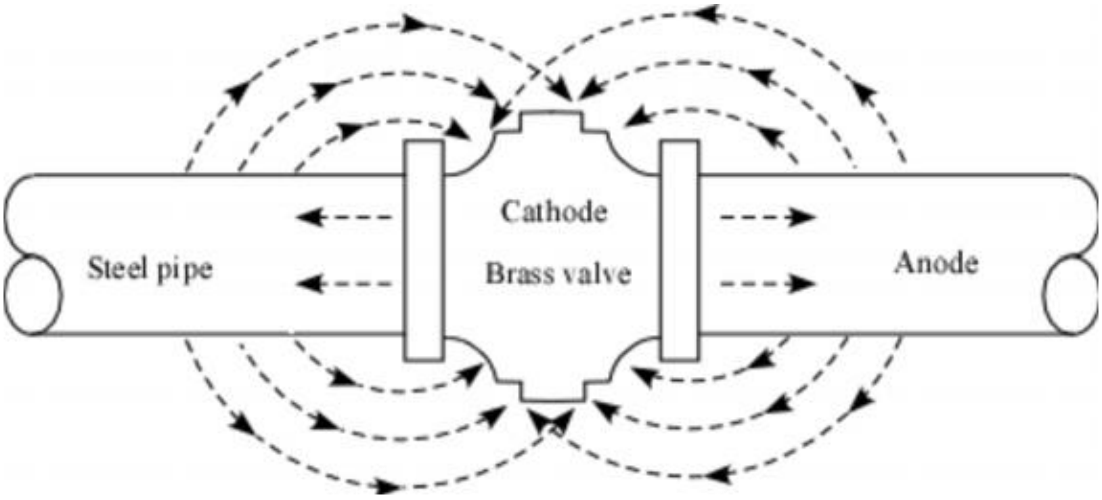

Figure (2-4) shows Corrosion Due to Dissimilar Metals examples [13].

2.3.4 Corrosion Due to Dissimilar Surface Conditions

Figure (2-5) Illustrates the condition of dissimilarity of pipe surface condition illustrates the condition of dissimilarity of pipe surface condition. Bright pipe metal such as scratches caused by pipe wrenches or shallow threads adjacent to couplings or fitting are anodic to the pipe surface. These cells can be very active due to the unfavorable ratio of anodic to cathodic areas [14].

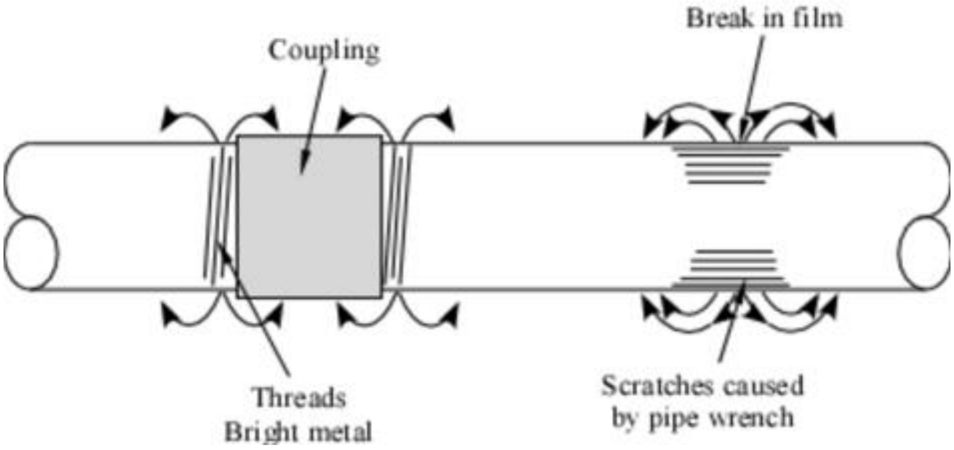

Figure (2-5) Illustrates the condition of dissimilarity of pipe surface condition [13].

2.3.5 Corrosion Due to Dissimilar Soils

Figure (2-6) the condition of two completely different soils or illustrates the condition of two completely different soils or electrolytes. The rate of corrosion is determined by the resistance of the soil. If the soil resistance is low, the rate of corrosion will be rapid [14].

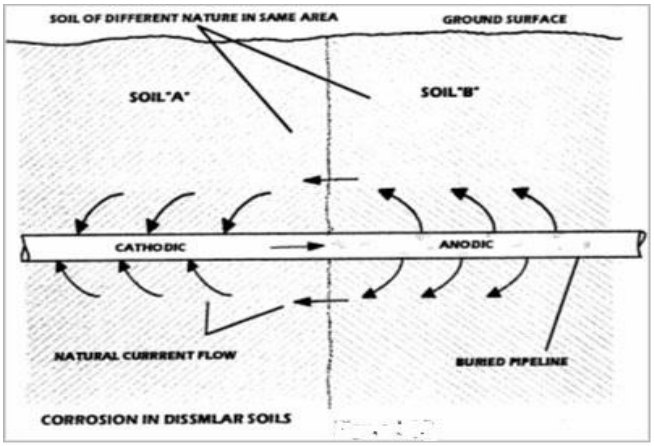

Figure (2-6) The condition of two completely different soils or electrolytes [13].

2.3.6 Corrosion Due to Differential Aeration of Soil

Figure (2-7) show the condition of a difference in aeration of illustrates the condition of a difference in aeration of soils. In this case, the soil throughout the depth of the trench is uniform, but the pipe rests on heavy moist undisturbed ground on the bottom of the ditch, while the rest of the pipe in contact with the drier backfill. The narrow strip of pipe in contact with the bottom of the ditch is the anodic area and the pitting can be very severe [14].

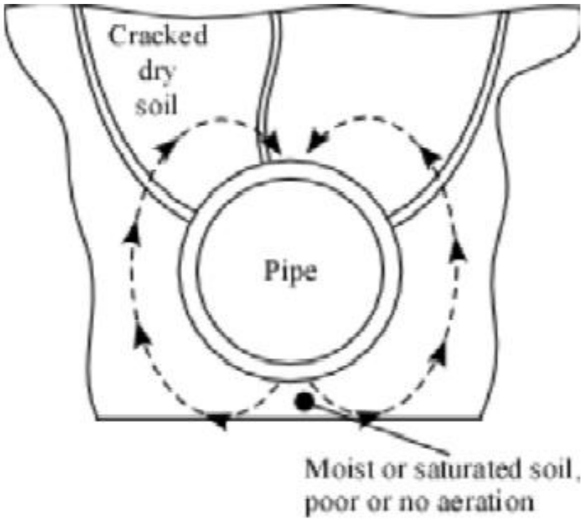

Figure (2-7) The condition of a difference in aeration of soils [13]

2.3.7 Stress Corrosion Cracking (SCC)

Stress corrosion cracking environmentally induced-delayed failure describes the phenomenon that can occur when many alloys are subjected to static, surface tensile stresses and are exposed to certain corrosive environments. Cracks are initiated and propagated by the combined effect of a surface tensile stress and the environment.

The stresses that cause SCC are either produced as a result of the use of the component in service or residual stresses introduced during manufacturing show in figure (2-8). Microstructure image of stress corrosion shows sample of microstructure image of stress corrosion cracking. And when stress corrosion cracking occurs, the environment is usually one in which the material exhibits good resistance to general corrosion [15].

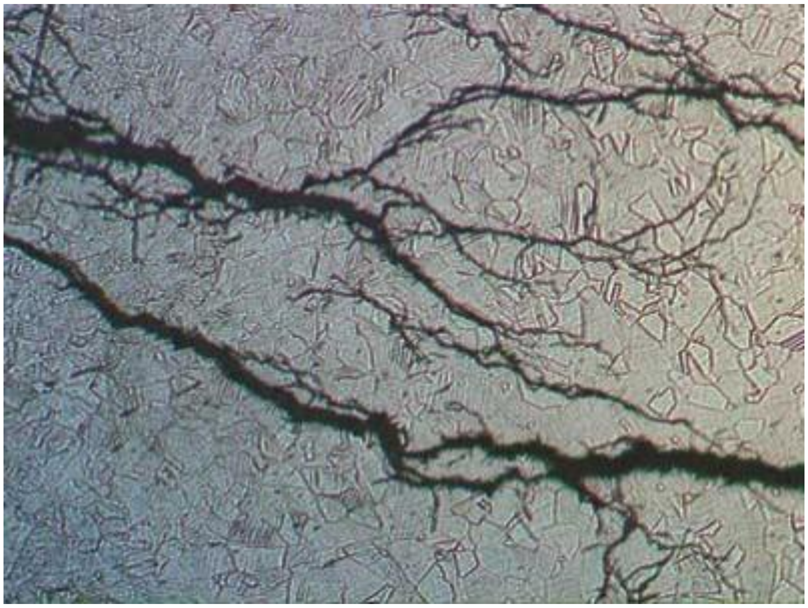

Figure (2-8) Microstructure image of stress corrosion cracking [11].

2.3.8 Crevice Corrosion

Crevice corrosion is a localized form of corrosion associated with stagnant micro environments that tend to occur in crevices, such as under gaskets, washers fastener heads, surface deposits, disbanded coatings, lap joints, and clamps .Limited oxygen diffusion into the crevice sets up a differential aeration cell between the crevice and the external surface. Reduction of oxygen cannot be sustained in the crevice which causes the crevice to be an acidic, anodic environment. Figure (2-9) shows the stages of a typical crevice corrosion process [15].

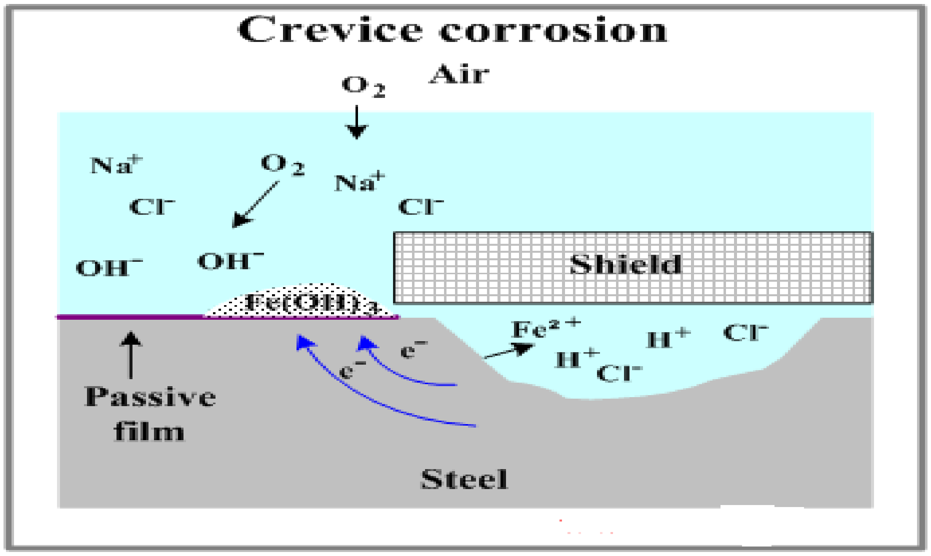

Figure (2-9) Propagation of Crevice corrosion [15]

2.3.9 Stray Current Corrosion

Stray current corrosion is caused by an earth path of direct current (DC) from a source external to an underground metallic structure as shown in Figure (2-10) Stray current. NOTE: On a direct current (DC) operated transit system; the sources are the rectifier substations, overhead catenary, trains and running rails [16].This corrosion is usually found after failures in the foreign structure occur. Stray current corrosion is the most severe form of corrosion because the metallic structure is forced to become an anode and the amount of current translates directly into metal loss. If the amount of current leaving a structure to enter the electrolyte can be measured, this can be directly translated into metallic weight loss. Different metals have specific amounts of weight loss when exposed to current discharge. This weight loss is normally measured in pounds (or kilograms) of metal lost due to a current of one Amp for a period of one year (one Amp-year). For example, if a stray current of just two Amps were present on a steel pipeline, the result would be a loss of 18.2 kilograms 40.2 pounds (of steel in one year [17].

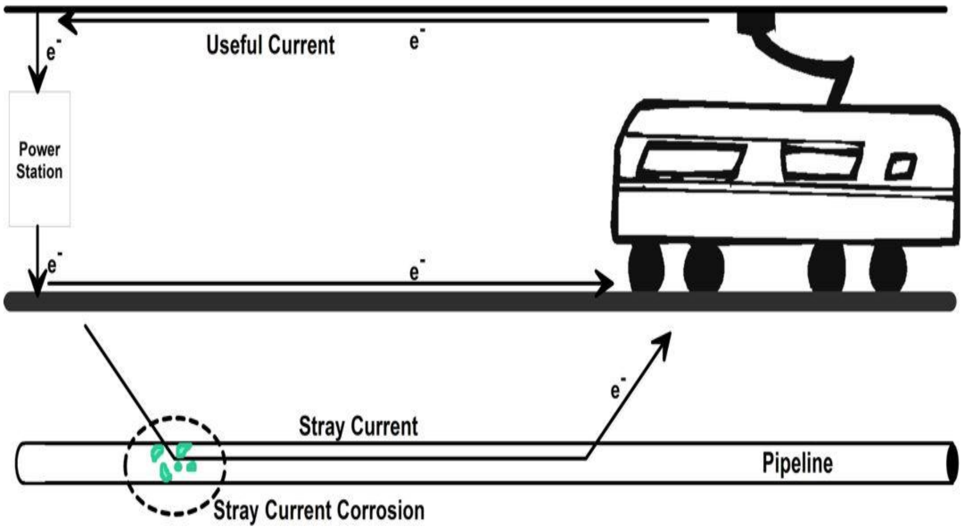

Figure (2-10) Stray current corrosion [18]

Table 2-1: Weight loss of specific metals at a current of one ampere for one year. [17]

Metal (Ion)	**Weight loss (kg)**	**Weight loss (pound)**
Magnesium	4.00	8.8
Aluminum	2.95	6.5
Zinc (Zn^{++})	10.66	23.6
Chromium	5.65	12.5
Cadmium	18.39	40.5
Iron (Fe^{++})	9.13	20.1
Cobalt	9.63	21.2
Nickel	9.58	21.1
Copper (Cu^{+})	20.77	45.6
Copper (Cu^{++})	10.39	22.8

2.4 Corrosion Control

There are five popular methods to control corrosion

2.4.1 Design

As an old adage says, corrosion prevention must start at the blackboard, at the design stage. A good design at the blackboard is no more costly than a bad design, a bad design is always more expensive than a good design in reality. Technical design includes the aspects of design that directly bear on the proper technical functioning of the product attributes that describe how it works and how it is made. Design configuration has a critical role to play in the service life of components. The important point is that the designers must have an understanding and awareness of 10 corrosion problems. Corrosion is, however, only one of the several parameters with which the designer is concerned and it may not be, however, important to a designer to give consideration to corrosion unless dictated by a requirement. In many instances, corrosion is incorporated in design of equipment only after its premature failure. More often, more attention is paid to the selection of corrosion resistant materials for a specific environment, and a minimal consideration is given to design, which leads to equipment failure. For instance, even a material, like 90-10 copper–nickel may fail prematurely as a condenser tube material, if the flow velocity of salt water or seawater is not given a due consideration for a smooth flow in the tube design. This has been a common observation in desalination plants in the Gulf region. This chapter would highlight how corrosion could be prevented by adopting good design practices [18].

2.4.2 Materials Selection

The world of materials comprises of polymers, metals, ceramics, glasses, natural materials and composites. Revolutionary developments have taken place in recent years because of the highly competitive materials market and emergence of new materials and new processing techniques. Selecting a corrosion resistant alloy would be the answer to corrosion problems. However, corrosion resistance is not the only property to be considered when selecting a material. Cost dictates the selection of materials [18].

2.4.3 Inhibitors

A corrosion inhibitor is a substance which when added in small quantities to a corrosive environment reduces the corrosion rate of the metal by action at or near the metal surface. Whether a substance is an inhibitor or not depends on the nature of both the metal and environment. It is convenient to classify inhibitors according to which electrode reaction they affect: anodic or cathodic [19].

2.4.4 Protective Coatings

The objective of a coating is to provide a barrier between the metal and the environment. Another advantage of protective coatings is that it is possible to combine the protective function with aesthetic appeal. Coating can be classified into Metallic and Non Metallic coatings [18].

2.4.5 Cathodic Protection

Cathodic protection is a method to reduce corrosion by minimizing the difference in potential between anode and cathode. This is achieved by applying a current to the structure to be protected (such as a pipeline) from some outside source, or current can be passed between the cathode and the anode due to the different in potential when enough current is applied, the whole structure will be at one potential; thus, anode and cathode sites will not exist. Cathodic protection is commonly used on many types of structures, such as pipelines, underground storage tanks, locks, and ship hulls [19].

2.5 The Principles of Cathodic Protection

The principle of cathodic protection is in connecting an external anode to the metal to be protected and the passing of an electrical DC current so that all areas of the metal surface become cathodic and therefore do not corrode. The external anode may be a galvanic anode, where the current is a result of the potential difference between the two metals, or it may be an impressed current anode, where the current is impressed from an external DC power source. In electro-chemical terms, the electrical potential between the metal and the electrolyte solution with which it is in contact is made more negative, by the supply of negative charged electrons, to a value at which the corroding (anodic) reactions are stifled and only cathodic reactions can take place. The current density and the potential are quite high and after applying ICCP the potential decrease with decreasing the current density as shown in Figure (2.11).[6]

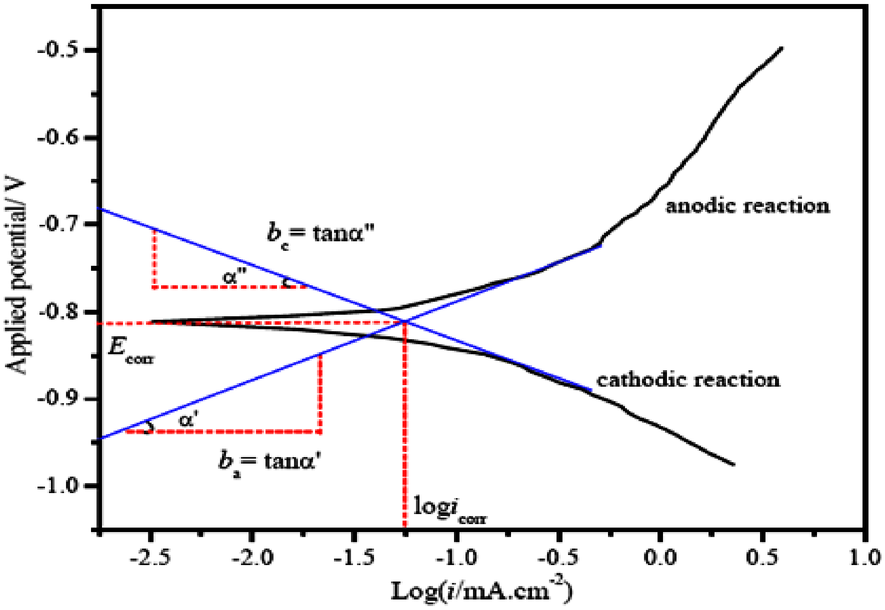

Figure (2-11) the Principle of Cathodic Protection [6]

2.6 Types of Cathodic Protection

There are two main types of cathodic protection systems; there are impressed current and sacrificial anode. Both types of cathodic protection have anodes, a continuous electrolyte from the anode to the protected structure, and an external metallic connection (wire). These items are essential for all cathodic protection systems.

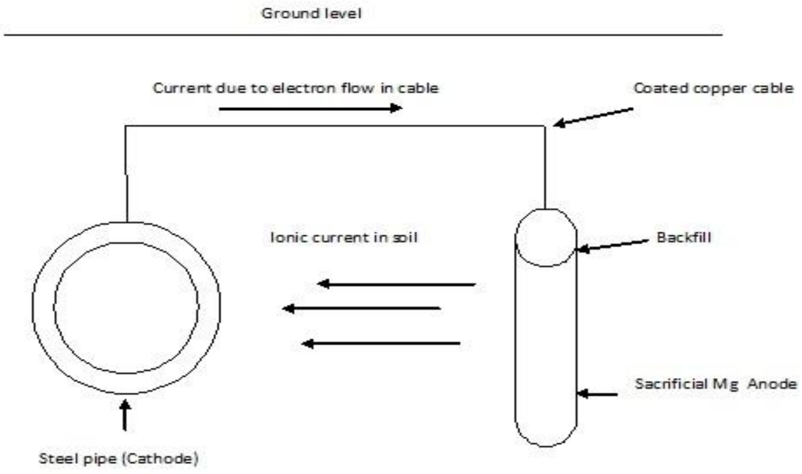

Figure (2-12) Principle of cathodic protection with sacrificial anodes [9]

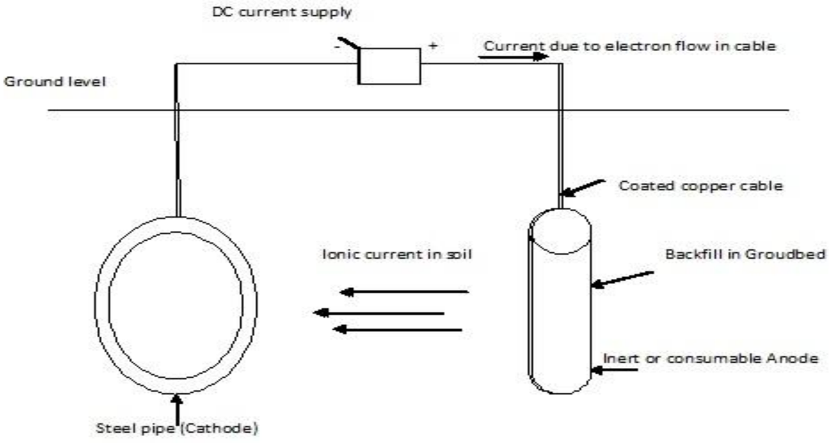

Figure (2-13) Principle of cathodic protection with impressed current [9]

As shown in Figure (2-12) and Figure (2-13), there are two major types of cathodic protection stations, each employing a different method of producing the protective current flow [9].

2.6.1 Sacrificial Anode Cathodic Protection SACP

A sacrificial anode cathodic protection system in Figure (2-12) makes use of the corrosive potentials for different metals. Without cathodic protection, one area of the structure exists at a more negative potential than another, and results the occurrence of corrosion on the structure. On the other hand, if a negative potential metal, such as Mg is placed adjacent to the structure to be protected, such as a pipeline, and a metallic connection is installed between the object and the structure, the object will become the anode and the entire structure will become the cathode. New addition object will be sacrificially corrodes to protect the structure. Thus, this protection system is called a sacrificial anode cathodic protection system because the anode corrodes sacrificially to protect the structure. Anodes materials in this system are usually made of either Mg or zinc because of these metals higher potential compared to steel structures [20].

2.6.1.1Applications [21]

Galvanic anode systems are utilized primarily for structures with limited surface area exposed to the soil and which are capable of being electrically isolated from grounding systems and other larger, bare metallic structures. This limitation is due to the limited current available from galvanic anodes (usually in milli-amperes). Typical applications for galvanic anode systems are:

1. Well-coated (new) oil gas distribution piping.
2. Steam distribution conduits.
3. Small, coated and electrically isolated fuel storage tanks.
4. Coated and electrically isolated fuel lines.

2.6.1.2Anode Materials

Anodes for galvanic systems may be zinc, magnesium or aluminum alloy. Table (2-2) contains data on the types of galvanic anodes. In most cases, magnesium is preferred for soils and fresh water. Zinc is generally limited to use in sea water, brackish water, sea mud and soil with resistivity below 1500 Ohm.cm. Zinc does not give available electromotive series (EMF) in soils with resistivity greater than 2000 Ohm.cm. And is, therefore, rarely used whilst magnesium is generally used in soils with a resistivity of less than 10,000 Ohm.cm. However, in soils with a greater resistivity, magnesium can be used for small-diameter service pipes. Where only small currents are required, occasionally, aluminum alloy can be used. For example, in buried sub-sea pipeline carrying hot fluids, zinc has been found to corrode to an unacceptably high level whereas aluminum alloys are more suitable [22].

Table (2-2) Capabilities and consumption rates of galvanic anodes [9]

Type	***Potential vs. SCE, mV***	***Ampere-hour, (per lb)***	***Consumption, lb/Ampere. Year***
Magnesium			
H-1 scrap alloy	1.4-1.5	250-470	19-35
AZ-63 alloy	1.5-1.6	500-580	15-38
High potential alloy	1.7-1.8	450-540	16-19
Zinc ASTM B418-73			
Type 1 (seawater)	1.10	354	24.8
Type 2 (soil)	1.10	335	26.2
Aluminum			
Mercury alloys	1.10	1250-1290	6.8-7.0
Indium alloys	1.17	1040-1180	7.4-8.4

2.6.1.3Advantages and Disadvantages of Galvanic Anode System [23].

Galvanic anode systems have a number of advantages:

1. No external power is required.
2. No regulation is required.
3. Easy to install.
4. Minimum of cathodic interferences problems.
5. Anodes can be readily added.
6. Minimum of maintenance required.
7. Uniform distribution of current
8. Minimum right-of-way / easement costs.
9. Efficient use of protective current.
10. Installation can be inexpensive if installed at time of construction.

Galvanic anode systems also have disadvantages that limit their application:

1. Limited driving potential.
2. Lower /limited current output.
3. Poorly coated structures may require many anodes.
4. Can be ineffective in high-resistivity environments.
5. Installation can be expensive if installed after construction.

2.6.2 Impressed Current Cathodic Protection

Impressed-current systems in Figure (2-13) employ inert (zero or low dissolution) anodes and use an external source of DC power (rectified AC) to impress a current from an external anode onto the cathode surface [24].

Table (2-3): Comparison between sacrificial anode system and Impressed Current System [25].

Sacrificial Anode System	Impressed Current System
It requires no external source	External power is essential
It can be easily installed and maintained	More complicated system for installation
It can be used in areas where the soil resistivity is low	Limited to use below a soil resistivity of 3000 ohms-cm
It is economical	Less economical for small structure
For small structures	For big structures

In addition to the structure to be protected and the electrolyte (soil, water, etc.), impressed current cathodic protection systems consist of the following essential components:

1. The current source, such as transformer/rectifiers, solar generators, etc.
2. The impressed current anodes buried in soil or immersed in water.
3. The interconnecting cables.

An ICCP uses a rectifier (an electrical device for converting alternating current into direct current) to provide direct current through anodes to the metal tank, piping, or other underwater components to achieve corrosion protection. The system may also be provided with a current control circuit to regulate the protection level. Such regulation is particularly useful when different structures are protected by the same current source [24].

Impressed current cathodic protection (ICCP) is widely employed in conjunction with surface coatings to control the corrosion of the underwater structures. The potential static ICCP systems normally fitted employ closed loop control in which the current output from a DC power supply is controlled via a reference electrode (RE) which measures surface potential in its vicinity. This potential is compared with the required protection value (set potential), typically 800 or 850 mV vs. silver/silver chloride or copper/copper sulfate System current output is then varied, via the driving voltage of the power supply, to maintain a zero error signal and hence a constant potential at the RE. Current output is thus controlled automatically in response to the operational conditions and the system is, therefore, demand-responsive. The processes involved in cathodic protection are essentially electrochemical phenomena at the interfaces between the water and the cathodic structure (and the anodic surfaces). ICCP system current output, as determined via the maintenance of the set potential in the vicinity of the RE, will be affected by a number of factors, such as surface condition, coatings and the presence or of flow [26].

2.6.2.1 Applications

Impressed current cathodic protection (ICCP) systems are utilized when the extent of the piping system or size of the structure is large, when there is no effective coating system, or when the structure cannot be isolated from grounding systems or other extensive bare piping networks. All of these systems or other extensive bare piping networks increase the current requirements for cathodic protection beyond the economical capabilities of the galvanic anode cathodic protection system. Examples of these applications of impressed current systems are as follows:

a. Bare piping systems (oil, gas, steam distribution).
b. Copper concentric neutrals of electric distribution cables-fueling systems.
c. Large fuel storage tank.
d. Large above grade storage tank bottoms.
e. Water storage tank interiors.
f. Wastewater process equipment.
g. Shore-side structures such as piers, docks, bulkheads.

This method of cathodic protection is a deliberately established electrolytic corrosion cell. The protection feature is obtained by setting the direction of current flow so that the protected structure is the cathode of the cell and some other material is the anode.

Present day impressed current systems use “rectifier” as the external source of current in the electrolytic cell. The rectifier is an assembly including a multi-tap alternating current (AC) step-down transformer, an arrangement of metallic rectifiers, a protective circuit breaker or fuse and output.

Rectifiers can be manufactured for a wide range of output voltage and current requirements. Power can be mains supply single or 3-phase, or from an alternative source such as: transformer rectifier, solar photovoltaic cell, thermoelectric generators, turbine generator units, and engine generator units, wind powered generators, diesel generators and gas generators.

These latter supplies are particularly appropriate in remote areas. Units can be oil or air cooled. Output control can be manual or automatic, to suit the application, varied according to a signal monitored from strikes near the pipeline. Surge arrestors are fitted across the DC output terminals [25].

2.6.2.2 Anode Materials

Anodes are connected in parallel and may be buried horizontally or vertically, surrounded by a carbonaceous backfill mixed with lime to reduce resistivity immediately around the anode. The backfill has the effect of increasing the anode surface area, reducing overall resistance.

The anodes of an impressed current system provide the means for the protective current to enter the electrolyte. Since the anodes form the corroding part of the system, the best material is one which has low rate of weight loss per ampere-year as shown in Table (2-4).

Table (2-4) electrochemical equivalents of common structural metals [27]

Metal	Weight-loss, lb/Ampere. Year
Aluminum	6.5
Carbon (Graphite)	2.2
Copper	22.8
Iron	20.1
Lead	74.5
Magnesium	8.8
Nickel	21.1
Silver	77.6
Tin	42.0
Zinc	23.6

The most commonly used materials for impressed current anodes are graphite and high-silicon cast iron. Aluminum is sometimes used in water storage tanks. In areas where heavy icing is not a problem, high silicon cast iron anodes are used instead of aluminum for lower long-term cost. Platinum coated titanium or niobium anodes are becoming more prevalent as impressed current anode material. The types of materials have specialized applications and when installation and operating costs are assessed, very few anodes can be used universally for any type of application and still achieve a desirable design life. In most soils, anodes evolve oxygen and the anode oxidizes as the current is discharged. In chloride containing soils or water, anodes evolve chlorine gas which forms hydrochloric acid and the anodes breakdown chemically. The whole purpose of this explanation is to point out that some anodes perform well in the presence of oxygen and others in the presence of acids [27].

2.6.2.2.1 High-silicon Cast Iron Anodes

Cast iron anodes are produced in two alloys types with the principal addition of chromium to improve the life in chloride soil and water. Table (2-5) shows the metallurgical composition of the two alloys.

The principal reason for superior cast iron performance is the formation of silicon oxide (SiO_2) film that forms on the anode surface, reducing the rate of oxidation and retarding the consumption rate. They have good electrical properties and resistance of the alloy.

Table (2-5) Cast iron compositions [27]

Element	**ASTM-518**	
	Grade 1	**Grade 2**
Silicon	14.2 - 14.75%	14.2 - 14.75%
Manganese	1.5% max.	1.5% max.
Chromium	-	3.25 - 5.0%
Carbon	0.75 - 1.15%	0.75 - 1.15%
Copper	0.50% max	0.50% max
Iron	Balance	Balance
Consumption Rate		
Soil	1 lb. /Ampere. Year	0.75 lb. /Ampere. Year
Seawater	18.5 lb. /Ampere. Year	0.25 lb. /Ampere. Year

To be successful in soil, the anodes are backfilled with metallurgical or petroleum coke breeze to reduce the anode resistance and increase the effective anode surface area. Even when the anodes are pre-packaged in coke breeze filled canisters, filling the annular space between the canister and the soil with additional coke breeze is a recommended practice. In seawater, the anode will discharge current at very low voltages compared to graphite rods [27].

2.6.2.2.2 Graphite Anodes

Graphite rods have been used as impressed current material for many years. The basic configurations consist of round or square rods. There are many types of graphite compositions and the type used for cathodic protection ground beds is the most porous one. The porosity allows moisture penetration to eventually migrate to the connection. Graphite should not be operated at current densities exceeding one ampere per 930 cm^2 in soil or 0.23 ampere per 1000 cm^2 in water. For optimum life in soil, most engineers design graphite anodes for a maximum density of 0.20 ampere per 930 cm^2. If the current density is within these ranges, the consumption rate will be approximately 0.9 kg per ampere year. Exceeding these limits, the material becomes mushy and is less conductive, due to chemical breakdown of the crystal boundary. Unfortunately, graphite is brittle and may be easily damaged during transportation, either bare or packaged. Special handling and padding are necessary to prevent cracking and breaking [28].

2.6.2.2.3 Aluminum Anodes

Occasionally, aluminum is used as an impressed current anode for protecting the interior of water tank, because it is relatively inexpensive compared to other impressed current materials [28].

2.6.2.2.4 Lead-silver Anodes

Lead alloy anodes are only used in free flowing seawater applications and may employ various metals such as antimony, lead, tin and 1 to 2 % silver. The consumption rate is about 0.09 kg per ampere-year and eventually a black, passive film of lead peroxide forms to extend the life of the anode surface, resulting in consumption of about 0.09 kg per ampere-year. Normal current density ranges from 3 to 25 amperes per 1000 $cm^{2.}$ In silty or low chloride conditions, this oxide film does not form and the anode is consumed rapidly [28].

2.6.2.2.5 Platinum Anodes

Platinum can be used as an anode coating for almost every type of cathodic protection installations. Structures in a vast array of environments such as underground, offshore, concrete structure, cathodic protection systems. Since platinum has such a low consumption rate, 8×10^{-6} kg per ampere-year, only a small amount is needed for a twenty year anode life. Pure platinum, by itself would be too expensive. The platinum is normally coated over noble base metals such as titanium and niobium. When anodes are in the form of wire and rods, there may be a copper core to increase the conductivity. The passive film on titanium starts to breakdown at 10 volts, anode-to-cathode potential and is limited to low resistance environments such as seawater.

Niobium has a breakdown voltage of 120 volts, power plants and the internals of piping, tanks and machinery have utilized platinum for anode-to-cathode potential and is used in higher resistance electrolytes. Current densities range from 50 amperes in soil to 500 amperes in seawater, depending on the anode surface area and thickness of the coating platinum has been coated on base metals using many techniques including sputtered, electrode position and cladding [29].

2.6.2.2.6 Ceramic and Mixed Metal Oxide Anodes [29]

Mixed metal oxide (MMO) anodes were developed in Europe during the early 1960’s for use in the industrial production of chlorine and caustic soda. The first known use of the technology for cathodic protection use occurred to protect a seawater jetty. These anodes exhibit favorable design life characteristics while providing current at very high density levels. The oxide film is not susceptible to rapid deterioration due to anode acid generation, rippled direct current.

Advantages of mixed metal oxide anodes are:

1. Light weight and unbreakable.
2. Negligible consumption rate.
3. Inert to acid generation.
4. Dimensionally stable.
5. High current density output.
6. Cost effective.

2.6.2.2.7 Polymer Conduction Anodes [30]

The material provides a small amount of current in restricted spaces such as internal pipe surface, heat exchangers, utility ducts and areas shielded from conventional ground bed current. The material resembles electrical cable but actually consists of a standard copper conductor with an extruded, conductive polyethylene jacket. This concept is used in underground concentric power cables as a conductive shield around the ground wires. The polymer contains carbon granules which discharge the current, leaving behind a polymer matrix. The anode should be backfilled in carbonaceous coke breeze for maximum life.

2.6.2.3 Advantages and Disadvantages of Impressed Current Systems [31]

Impressed current systems have a number of advantages:

1. Can be designed for a wide range of voltage and current.
2. High ampere-year output is available from signal ground bed.
3. Large areas can be protected by single installation.
4. Variable voltage and current output.
5. Applicable in high-resistivity environments.
6. Effective in protecting uncoated and poorly coated structures.

Impressed current systems have disadvantages which limit their application:

1. Can cause cathodic interference problems.
2. Are subject to power failure and vandalism.
3. Have right-of-way restrictions.
4. Require periodic inspection and maintenance.
5. Require external power, resulting in monthly costs.
6. Overprotection can cause coating damage.

2.7 Cost and Economic Aspects of Cathodic Protection

Over the years the cost of implementing a corrosion control system has proven to be extremely beneficial in the reduction of leaks and extension of the useful life of pipelines [32]. The additive cost for corrosion control typically represents a very small percentage of initial pipeline construction costs. With this in mind corrosion control system by cathodic protection should be implemented as a standard operating procedure for all buried pipelines system to enhance the life of the asset. The effectiveness of cathodic protection for the full and long-term repair of corrosion-damage buried pipelines- is now well established. However, for the technique to develop and flourish into a mature and commercially successful repair strategy it must be seen to be both technically and economically attractive. As the number of installation increases, the opportunity exists to judge how the expectations compare with reality. Overall, the comparison is favorable with significant cost savings being reported compared with conventional repair. Comparing leak cost and cathodic protection system cost is a good example

of economic consideration for the cathodic protection systems. When a section of pipeline system starts to develop leaks, experience has shown that further leaks will develop at continuously increasing rate. If the accumulated number of leaks repaired is plotted on semi-log paper against pipeline age in years, a straight line is the usual result where accurate leak records are available as shown in Figure (2-14) [32].

In this instance, the first leak did not develop until the line was 4-years old and a total of only seven leaks had developed by the time the pipeline was 12-years old. A definite trend has been established, which shows that in the next 10-years there will be approximately 70 new leaks, if corrosion is not controlled. The figure is also shows that the number of leaks developing each year is increasing at such rate that the pipeline may become inoperable if the trend is not stopped.

The application of cathodic protection system as shown in Figure (2-14) can mitigate development of new leaks. The cost of operating a cathodic protection system versus the cost of leaks over a period of time can then be economically evaluated. In the case illustrated in Figure (2-14), application of cathodic protection at the end of the 12th year would eliminate approximately 70 new leaks over the next 10-years period.

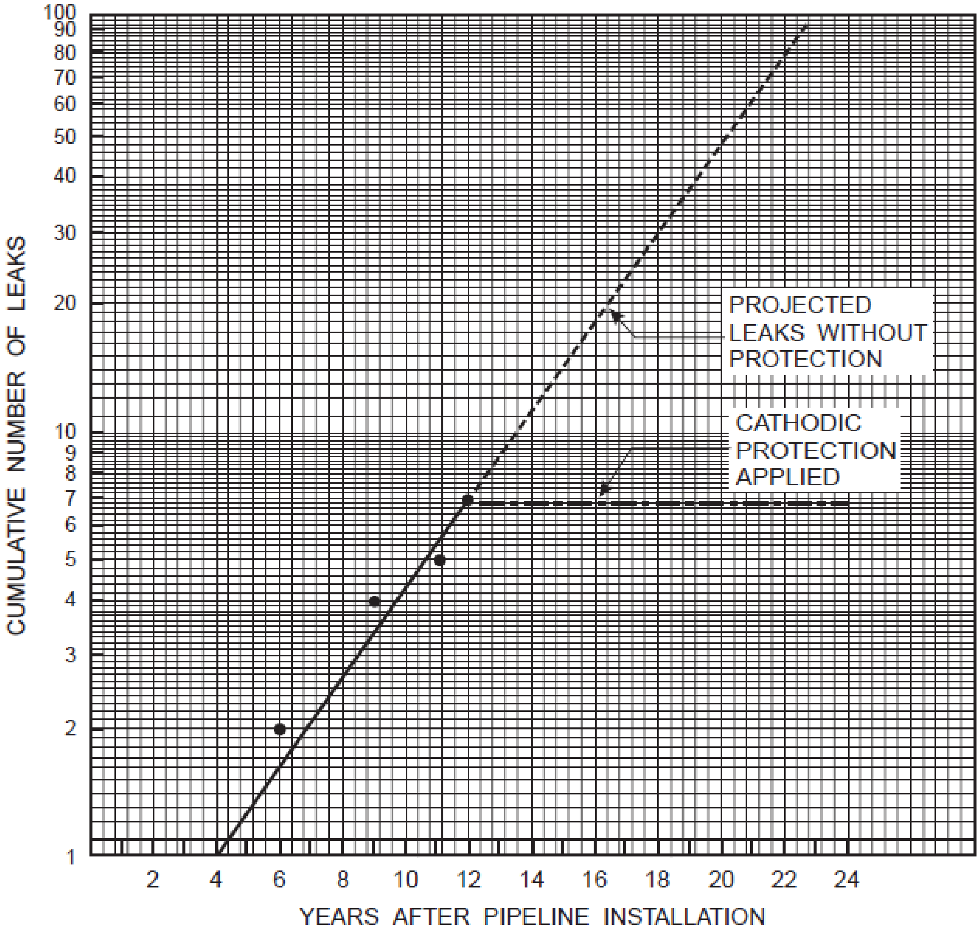

Figure (2-14) Cumulative numbers of leaks without cathodic protection [32]

Now assume that a coated pipeline having the leak record represented by Figure (2-14) is surveyed during its 12th year and those design calculations indicate that cathodic protection can be applied using rectifier system. Further assume that the annual cost of the investment of cathodic protection plus annual operating costs will be $ 6000 per year and it has been established that the average total cost of each leak repaired is $ 1500. Using these figures, if cathodic protection system is applied at the end of the 12th year, comparative costs for the following 10-years period are as follows:

- Cathodic protection costs: 10 × $ 6000 = $ 60,000
- Savings in leak repair costs: 70 × $ 1500 = $ 105,000

This example indicates that, over the 10-years period, there will be net savings of $ 45,000 with cathodic protection system installed, if all leaks are avoided [32].

Chapter Three

Cathodic Protection Model

3.1 Historical Background

The idea of mathematically predicting the electrolytic corrosion behavior for a physical situation had its genesis at least six decades ago. A number of very fundamental and mathematically definitive papers appeared in the literature in the early forties predicting current distributions for plane electrodes and assumed linear polarization. Various theoretical treatments on this subject were published in the 1950’s addressing coplanar electrode configurations with varying degrees of polarization effects. These analyses were generally limited to one dimensional effort in cartesian coordinate systems with simplified polarization effects. A mathematical analysis of cells with unequal polarization parameters demonstrated the treatment of slightly more complex geometry in the presence of more realistic polarization effects. In all of these mathematical treatments, the Laplace equation was the governing field equation with the additional assumption that the electrolytic medium and the electrode materials possessed constant electrical properties. The concepts of modeling continuous linear D.C. electromagnetic spaces using the finite element method was proposed in the late 1960’s. The idea of expressing the multielectrode electrochemical relations for a continuum in terms of the Laplace equation had its origin in the numerous publications of Wagner and Kasper [33]. To solve the electrochemical equations via a time independent heat transfer analysis already in existence was suggested in the mid 1970s for large scale structures focusing on macroscopic electric field effects without directly integrating the local polarization effects or surfaces. The first extensive study to include generally realistic polarization effects using finite element methods for two dimensional electrode/electrolytic spaces was first completed in 1977 and finally released for publication in 1981. Since then, the methods with more application in cathodic protection and other areas are the (FEM) finite element method and the (BEM) boundary element method, using simplifications in the electrolyte (homogeneous medium) [33]. The work of Munn and Devereux [34], is very important in the use of FEM for numerical modeling of galvanic corrosion systems, they have used a commercially heat conduction computer program for electrochemical analysis, because of the analogy between electrical and thermal conduction, this program was modified by programming for the particular boundary conditions representing non linear electrode kinetics. The Computational Mechanics BEASY group was the first to apply boundary element technology to corrosion applications and the first to develop commercial tools capable of modeling large-scale structures. The value of the technique was demonstrated by its application to the Conoco TCP platform in the early eighties. They developed the software Beasy CP and SeaCorr CP based on these early developments. During the development of SeaCorr CP, the transient representation of kinetics was developed with CorrOcean of Norway and the support of Conoco [35]. Dan Townley at Chevron has been engaged in CP modeling and applications since 1980. He has developed design approaches for CP of complex structures such as the risers of an offshore petroleum production spar. The unusual and restricted geometry of this system requires more detail than conventional offshore CP design [36]. To simplify the BEM calculations, he developed a unified design equation based on a linearized polarization curve for the electrochemical reactions involved [37]. Virginia DeGiorgi at the U.S. Naval Research Laboratory conducts modeling for naval applications, including evaluation of properties and performance of smart materials, fracture fatigue of metals, and, since 1990, cathodic protection of complex structures such as the hulls of ships. Her group was the first to provide detailed comparison between boundary-element calculations for CP of ships and experimental results using scale models [38]. The group of Professor Shigeru Aoki began research on application of BEM to CP problems in the early 1980. They were the first to perform an experimental verification of BEM results for a complicated real-life structure. They have developed a BE optimization method for CP to minimizing the power supply under the protecting condition which is taken into account by the penalty function method. They use a multipeaked cost function which is coped with a genetic algorithm combined with the conjugate gradient method. They were the first to apply BEM to solve inverse problems in CP [38].

3.2 Experimental models

3.2.1 Abdullatif Model [39]

Two equations governing and controlling the relationship between the total current and the soil conductivity values were drawn and derived by Mohammed O. M. Al-Abdullatif (2007). These mathematical functions were defined within two main conductivity zones as per the following Equations:

$$I = c_1 \times \kappa \qquad \text{Where } 2 \leq \kappa \leq 60 \qquad \ldots (3\text{-}1)$$

$$I = c_2 \times e^{C3 \times \kappa} \qquad \text{Where } 120 \leq \kappa \leq 61 \qquad \ldots (3\text{-}2)$$

Where:

I = Total current required in mA

e = Exponential function

κ = Soil conductivity in mS/m

c_1 = Constant in (mA. m/mS) depends on the boundary conditions

c_2 = Constant in (m/mS) depends on the boundary conditions

c_3 = Constant in (m/mS) depends on the boundary conditions

After solving the above equations and considering the polarization data for the cathode and anode as the boundary conditions, the following two empirical Equations were obtained:

$I = 237 \times \kappa$ Where $2 \leq \kappa \leq 60$ …(3-3)

$I = 1895 \times e^{0.0373\, x\, k}$ Where $120 \leq \kappa \leq 61$ … (3-4)

It is very clear from the above two equations that, the total current increased due to increase in soil conductivity. On the other hand, when the soil conductivity is decreased, soil ohmic resistance increases and, as a result, totals current decreases. In the second interval Equation (3-4), surface kinetics dominates and a secondary current distribution is obtained, and this means that, the current required to perform the protection will not be an infinite value due the formation of deposits on the pipe surface. While, primary current distribution is obtained, in the first interval where Equation (3-3) is valid. Moreover, the above two equations are valid only for a pipeline with a total length of 7500 m and 8 anodes. In another word, the coefficients of these equations are dependent on the boundary conditions of the system, and the formation of surface deposits on the pipe. Figure (3-1) and Figure (3-2) is describing the relationship between the soil conductivity and total current required according to the above two Equations [39].

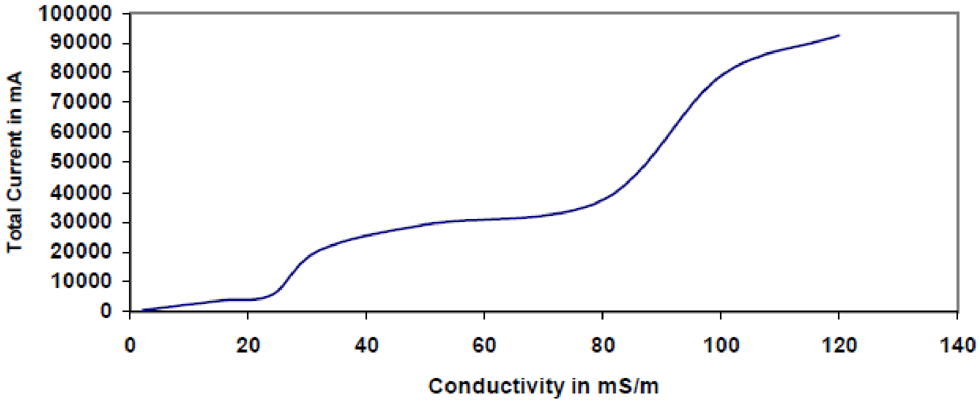

Figure (3-1) The relationship between soil conductivity (resistivity) & given current for cathodic protection system (initial data) [39].

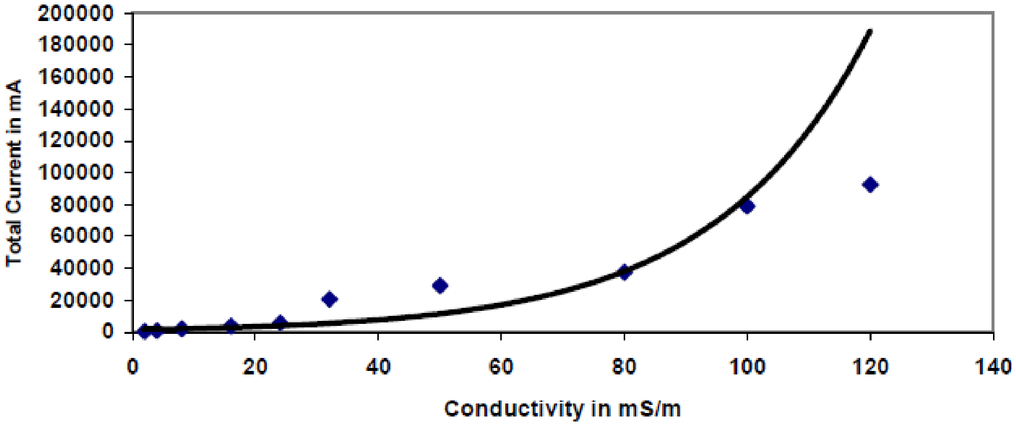

Figure (3-2) The relationship between soil conductivity (resistivity) & given current for cathodic protection system (trend line curve) [39].

3.2.2 Kakuba Model [40]

Godwin Kakuba (2005), presented a simplified model of the ICCP on a ship in sea water, ship considered a cuboid, The shapes of the electrodes are also assumed rectangular, for the domain, instead of considering the three layers of air, seawater and the seabed as described in Figure (3-3)

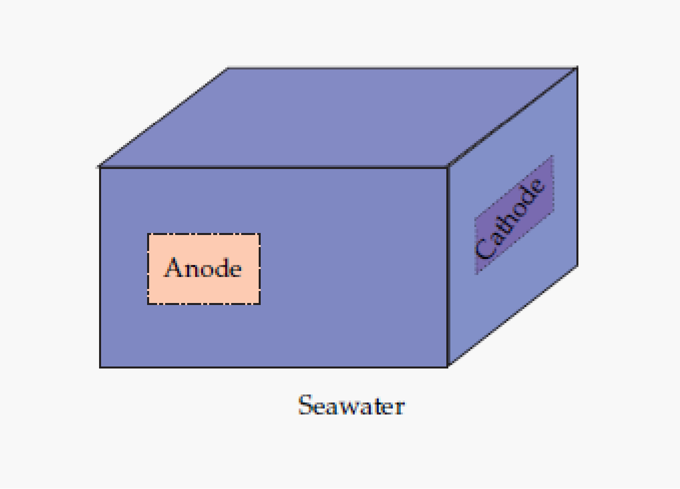

Figure (3-3) simplified model of the ICCP on a ship [40]

The boundary conditions we shall consider linear boundary conditions at the electrodes, Godwin Kakuba used this function:

$$f = {}^{1}/_{r}, r = \sqrt{(x-2)^2 + (y-5)^2 + (z-3)^2} \qquad \ldots (3\text{-}5)$$

Where (x, y, z) are the coordinates of the vertices of the j-th integration triangle. The BEM was then used to compute the values of $\partial f/\partial n$ at the surface and subsequently the values of f at some points outside the box. For the Neumann problem, values of $\partial f/\partial n$ were prescribed and for the mixed boundary value problem, values of f were prescribed at the electrode surfaces and $\partial f/\partial n$ at the rest of the surface. His experiments showed that for a symmetric problem the potential distribution is also symmetric and so is the current distribution. The potential fell monotonically away from the ship. The results also showed that, with linear boundary conditions, the magnitude of the current flow at the anode is not equal to that at the cathode. However, the two were the same in case of symmetric boundary conditions [40].

3.2.3 Abd Al-Rahman [41]

Haider Mijed Abd Al-Rahman (2009), found a relationship between cathodic protection current density, distance between anode and cathode and environment resistivity from data representation in Figure (3-4) as follows:

$$\boldsymbol{i_{cp}} = \frac{D}{A+B\,\rho^2} \qquad \dots (3\text{-}6)$$

Where:

$\boldsymbol{i_{cp}}$ = cathodic protection current density, mA/cm^2

D = distance between anode and cathode, cm

ρ = environment resistivity, Ω. cm

A = constant (0.2104)

B = constant (0.864×10^{-6})

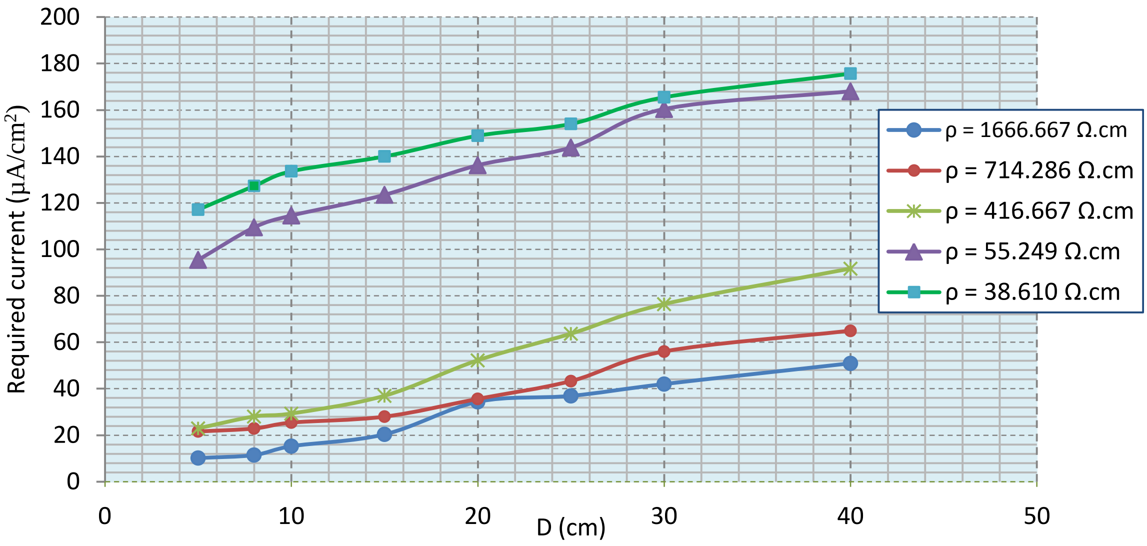

Figure (3-4) Distance between anode and cathode center versus required current for different environment resistivities [41]

3.2.4 Hliyil model [42]

Mohammed Hliyil Hafiz, (2006), found a new equation model for general protection potential which is especially suitable for structures in seawater:

$$\Delta V = 0.171 \times \left(\frac{\rho \times i}{D}\right) \qquad \ldots (3\text{-}7)$$

Where:

ΔV=difference in voltage versus SCE, V

ρ= environment resistivity, Ohm.cm

i=current through pipeline, ampere

D=distance between anode bed and pipe.

Hliyil Equation was examined in different fields and gave exact potential calculated, values as much as possible to the level of the potential values obtained through inspection as shown in Figure (3-5) which covers Iraqi-Turkish pipeline. Laboratory test results given in Figure (3-6) explained three environment resistivities as applied in this equation. Hliyil also found the relationship between cathodic protection voltage, current density and environment resistivity is given by computation. Equation using Hooks-Jeeves and Quasi-Newton methods.

$$V = a + c\,(\frac{\rho}{i})^k \qquad \dots (3\text{-}8)$$

Where:

V= voltage of pipe versus SCE
ρ= environment resistivity, Ohm.cm
i= current density, μA/cm^2
a, c and k are constants

The mathematical regression using Hooks-Jeeves and Quasi-Newton methods gives a=-1.355, c=0.330 and k=0.102 with correlation coefficient 0.9005 and standard error 2.2%. On the other hand, voltage for coated pipe with polyethylene tape is given by using Equation:

$$V = b + e\,(\frac{\rho i}{D})^h \qquad \dots (3\text{-}9)$$

Where:

V= voltage of pipe versus SCE
ρ= environment resistivity, Ohm.cm
i= current density, μA/cm^2
D= distance between pipe and anode
b, e and h are constants

The mathematical regression using Hooks-Jeeves and Quasi-Newton methods gives b=123.95, e= -1124.8 and k=0.06 with correlation coefficient of 0.9471 and standard error of 1.10 % [42].

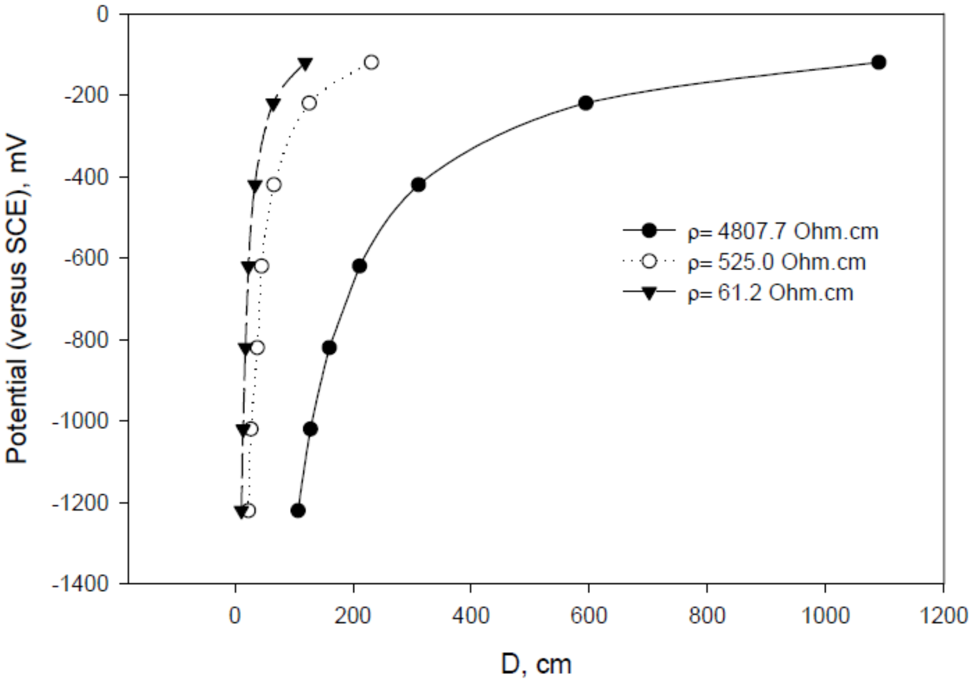

Figure (3-5) effect of potential versus SCE for different environment resistivities at 30C^0 [42].

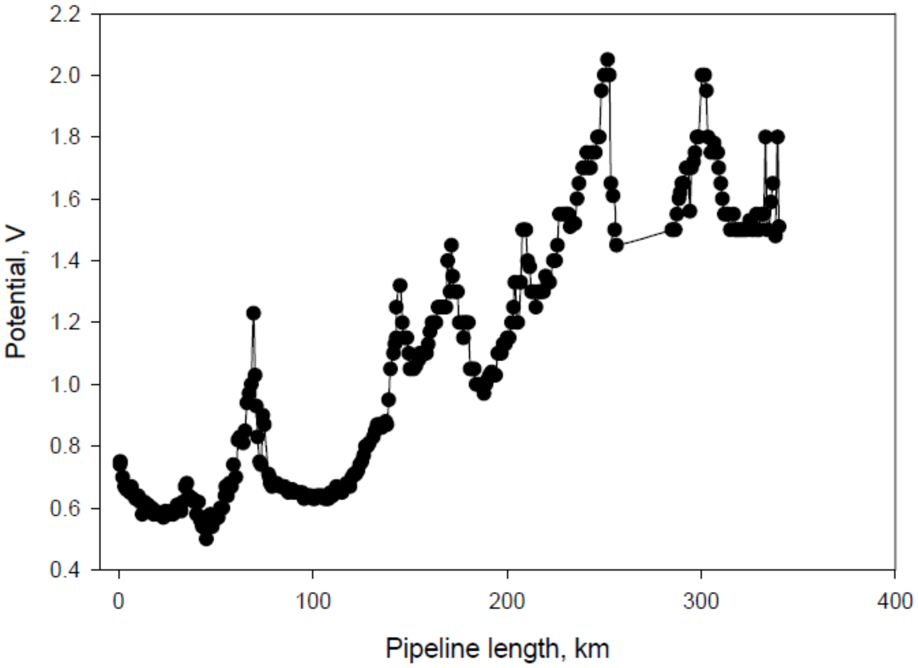

Figure (3-6) cathodic potential versus pipeline length for 4800 Ohm.cm environment resistivity at 25000 mV [42].

3.2.5 Jeffers model [43]

Kenneth Jeffers work in electrochemical impedance spectroscopy measurements were performed to monitor surface film formation and changes in charge transfer reaction kinetics. Statistical models were regressed to impedance data to identify nonstationary behavior and to estimate the stochastic error structure of the measurements. A process model for the impedance response was developed by considering contributions to the total current flow within the cell and diffusion of reacting species.

Electrochemical systems involving time dependent film formation usually exhibit non-stationary behavior during the time required to generate an impedance spectrum. Impedance data collected under non-stationary conditions will fail to satisfy the Kramers- Kronig relations. Since most process models applied to impedance spectra assume the steady-state, it is important to determine whether the collection time was short enough to model the system as stationary. A statistical technique of regressing measurement models to impedance spectra has been developed for filtering out non-stationary behavior [44]. The measurement model takes the form of the line shape based on the Kramers-Kronigconsistent Voigt circuit see Figure (3-7) with impedance given by:

$$Z(\omega) = Z_0 + \sum_K \frac{R_K}{1+j\,\tau_k\,\omega} \tag{3-10}$$

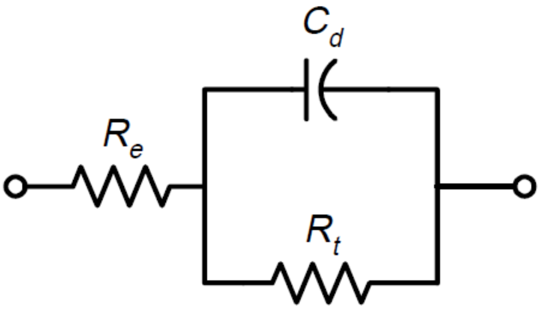

Figure (3-7) Schematic diagram of a circuit containing a resistor in series with a Voigt circuit [45].

Where Z_0 represents the high frequency impedance or electrolyte resistance, is a resistance parameter, and τ_k is an *RC* time constant. The technique follows an iterative procedure of adding successive line shapes to the model followed by regression to the data. The confidence intervals for the parameter estimates are calculated, and the number of parameters, necessary to fit the spectra, is constrained by the requirement that the 95.4% confidence intervals for each parameter must not include zero. The measurement model regression technique is also used to determine the nature of the experimental errors. The residual errors between the data and the model consist of systematic and stochastic contributions,ε_{sys} and ε_{stoch}, respectively. The systematic errors consist of lack of fit errors, ε_{lof} due to inadequacies of the model, and bias errors, ε_{bias} associated with nonstationary behavior, ε_{ns} and instrumental artifacts ε_{ins}. Thus, the experimental errors at any frequency can be expressed as:

$$Z - \hat{Z} = \varepsilon_{lof} + (\varepsilon_{ns} + \varepsilon_{ins}) + \varepsilon_{stoch} \qquad \dots (3\text{-}11)$$

Where is the model value for the complex impedance Z [46]. The approach is to collect consecutive pseudo-replicate impedance spectra and to regress the measurement model to each scan separately. By fitting the same number of line shapes to each replicate, the nonstationary error contribution is effectively filtered out as the regressed parameter values are adjusted for each individual scan. The errors due to instrumental artifacts are assumed to be constant from one experiment to another, and since one model was regressed to each replicate data set, the lack of fit error contribution is also constant. Another assumption stipulates that the stochastic errors $\varepsilon_{stoch} = \varepsilon_{stoch}, r + j\varepsilon_{stoch}, j$, are normally distributed with mean $\varepsilon=0$.

3.3 Boundary element method for underground pipe line

A cathodic protection system consists of three parts. First is the structure to be protected (cathode), second is the anode which provides the protection, and the third is electrolyte (e.g. soil). There are two general types of anodes in normal use. Sacrificial anodes usually made of zinc, aluminum alloys or similar materials which are more active in the galvanic series than iron or steel. The sacrificial anode therefore, corrodes in place of the protected structure. Impressed current anodes apply a potential difference by means of an external power supply [47].

During the electrochemical corrosion process, several anodic (oxidation) and cathodic (reduction) reactions occur when the structure is placed under the control of a suitable cathodic protection system; the anodic (corrosion) reactions are transferred from the structure to the sacrificial or impressed current anodes. This electrochemical process reverses the flow of current and the structure surface becomes the cathode. In the case of sacrificial anodes (i.e. zinc), the anode metal simply dissolves due to the inherent potential difference between the anodes and the structure. However, using “inert”, impressed current anodes causes a gas evolution reaction (i.e. hydrogen) to occur on the anode (without loss of material) and the familiar protective, cathodic reaction occurs on the structure. A further important concept in cathodic protection is that there is a minimum potential (thermodynamically reversible potential) $E_\circ$ which must be exceeded before any reaction occurs (and consequently before any current can flow). To describe a cathodic protection system mathematically, not only must the equations, which represent the flow of current through the medium (i.e. soil), be developed but also the equations, which represent the electrode reactions [28].

3.4 Mathematical aspect of the Boundary Element Method

The mathematical model of corrosion and cathodic protection based on Boundary Element Method has been applied to the field to quantify the protection potential and current density the current density can be defined as [48]

$$\boldsymbol{I}j = -F\sum_{i=1}^{N} \mathrm{z}_i D_i \frac{\partial c_\mathrm{i}}{\partial X_i} - F^2 \sum_{i=1}^{N} z_i^2 c_i u_i \frac{\partial \mathrm{E}}{\partial X_\mathrm{i}} \qquad \dots (3\text{-}10)$$

Where $\boldsymbol{I}j$ is the component of the current density vector; F is Faraday's constant; z_i ,c_i, u_i and D_i are the charge, concentration, mechanical mobility and diffusion coefficient, respectively. For species *i,* N is the number of species and *E* is the electrochemical potential. Defining the conductivity of the electrolyte in the form [48].

$$k = F^2 \sum_{i=1}^{N} z_i^2 c_i u_i \qquad \dots (3\text{-}11)$$

The above Equation reduces to:

$$\boldsymbol{I}j = -F\sum_{i=1}^{N} \mathrm{z}_i D_i \frac{\partial c_\mathrm{i}}{\partial X_i} - k\frac{\partial \mathrm{E}}{\partial X_\mathrm{i}} \qquad \dots (3\text{-}12)$$

The first term of the above equation represents the portion of current density sustained by concentration gradients, and this term can be neglected in large scale simulations, because concentration gradients exist only in the diffusion layer which is very thin compared to the size of simulation domain. Therefore, the current density in the electrolyte is then given by:

$$\boldsymbol{I_j} = -k\frac{\partial \mathrm{E}}{\partial X_{\mathrm{i}}} \qquad \text{Current density in electrolyte} \qquad \dots (3\text{-}13)$$

Conservation of charge gives:

$$\frac{\partial \mathrm{Ij}}{\partial X_{\mathrm{i}}} = \frac{\partial}{\partial X_{\mathrm{i}}}\left(-k\frac{\partial \mathrm{E}}{\partial X_{\mathrm{i}}}\right) = 0 \qquad \dots (3\text{-}14)$$

If the conductivity *k* is constant e.g. seawater so the above equation reduces to a Laplace equation for the electrochemical potential *E* [49]

$$k\nabla^2 E = 0 \qquad \dots (3\text{-}15)$$

The above equation is the governing equation for the potential distribution in an electrolyte.

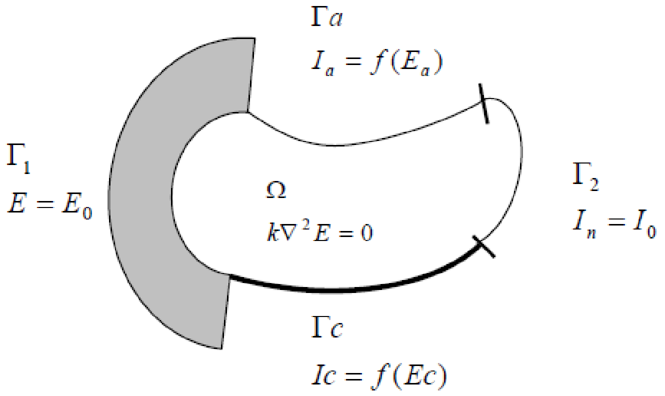

Figure (3-8) Governing equation and boundary condition [48], [50].

Consider that the CP system is designed within a homogeneous electrolyte J, surrounded by a boundary $\Gamma(\Gamma_1 + \Gamma_2 + \Gamma_a + \Gamma_c)$ as shown in the Figure (3-8) where the electrochemical potential *E* or current density *I* are prescribed on Γ_1

and Γ_2 respectively, while Γ_a represent the anode surface and Γ_c is the cathode surface. The boundary condition is

$E = E^{\circ}$ On Γ_1
$I_n = k\frac{\partial \mathrm{E}}{\partial \mathrm{n}} = I_{\circ}$ On Γ_2
$\mathrm{I_a}$, $\mathrm{E_a}$ unknown On Γ_a
$\mathrm{I_c}$, $\mathrm{E_c}$ unknown On Γ_c

We wish to solve equation (3-15) numerically as follows [50]:

$$c(\xi)\mathrm{E}(\xi) = \int_{\Gamma} \mathrm{E}(\xi,\mathrm{x})\mathrm{I_n}\, d\Gamma(\mathrm{x}) - \int_{\Gamma} \mathrm{I}(\xi,\mathrm{x})\mathrm{E}(\mathrm{x})\, d\Gamma(\mathrm{x}) \qquad \ldots (3\text{-}16)$$

Where E (ξ, x) and I (ξ, x) are the fundamental solution for the potential and current density respectively and the free term c (ξ) depends on the boundary geometry at the source point ξ.

$$E\ (\xi,\mathrm{x}) = \frac{1}{4\pi k r} \qquad \ldots (3\text{-}17)$$

$$I\ (\xi,\mathrm{x}) = k\frac{\partial \mathrm{E}^*}{\partial \mathrm{n}} \qquad \ldots (3\text{-}18)$$

Where r is the distance from the point $\mathrm{x_i}$ of application of the delta function to any point under consideration. Since the boundary Γ is discretized into approximated number of boundary elements N [50].

$$c_i E_i + \sum_{j=1}^{N} Ej \int_{\Gamma} I^* d\Gamma\mathrm{j} = \sum_{j=1}^{N} Ij \int_{\Gamma} E^* d\Gamma\mathrm{j} \qquad \ldots (3\text{-}19)$$

Where $\int_{\Gamma\mathrm{j}}$ represents integration over element j .The terms $\widehat{H}ij$ and Gij are obtained as follows [50].

$$\hat{H}ij = \int_{\Gamma} I^{*} d\Gamma\mathrm{j} \quad \ldots (3\text{-}20)$$

$$Gij = \int_{\Gamma} E^{*} d\Gamma\mathrm{j} \quad \ldots (3\text{-}21)$$

And

$$Hij = \hat{H}ij + ci\delta_{ij} \quad \ldots (3\text{-}22)$$

Where δ_{ij} is the Kronecker delta $\delta_{ij} = \begin{cases} 1, if\ i = j \\ 0, if\ i \neq j \end{cases}$

The following algebraic system is obtained [50]

$$\sum_{j=1}^{N} HijE = \sum_{j=1}^{N} GijI \quad \ldots (3\text{-}23)$$

If equation (3-23) is applied to all nodal points along the boundary, the following equation is obtained:

$$HE = GI \quad \ldots (3\text{-}24)$$

Where ***H*** and ***G*** are square matrices of influence coefficient, ***E*** and ***I*** are vectors of nodal values of potential and current density. Some of the elements of the vector ***E*** and vector ***I*** are known while some are unknown. By arranging all known on the right hand side and all unknowns on the left, the following matrix equation is obtained [49].

$$AX = B \quad \ldots (3\text{-}25)$$

To partition the *E* and *I* vectors (matrices (3-24)) into those nodes which form the anode and those which form the cathodes as follows [49].

$$\begin{bmatrix} Haa & Hac \\ Hca & Hcc \end{bmatrix} \begin{bmatrix} Ea \\ Ec \end{bmatrix} = \begin{bmatrix} Gaa & Gac \\ Gca & Gcc \end{bmatrix} \begin{bmatrix} Ia \\ Ic \end{bmatrix} \quad \ldots \text{(3-26)}$$

(a) refers to anode surface and (c) refers to cathode surface

$$\begin{aligned} Ia &= f(Ea) \\ Ic &= f(Ec) \end{aligned} \quad \ldots \text{(3-27)}$$

Substituting Equation (3-25) [49]:

$$\begin{bmatrix} Haa & Hac \\ Hca & Hcc \end{bmatrix} \begin{bmatrix} Ea \\ Ec \end{bmatrix} = \begin{bmatrix} Gaa & Gac \\ Gca & Gcc \end{bmatrix} \begin{bmatrix} f(Ea) \\ f(Ec) \end{bmatrix} \quad \ldots \text{(3-28)}$$

The resulting equation (3-28) is solved by iteration in Figure (3-8) to obtain the current density *I* and potential *E* at all nodes on the anode and cathode.

3.5 Flow chart of the iteration algorithm in solving a cathodic protection problem using BEM

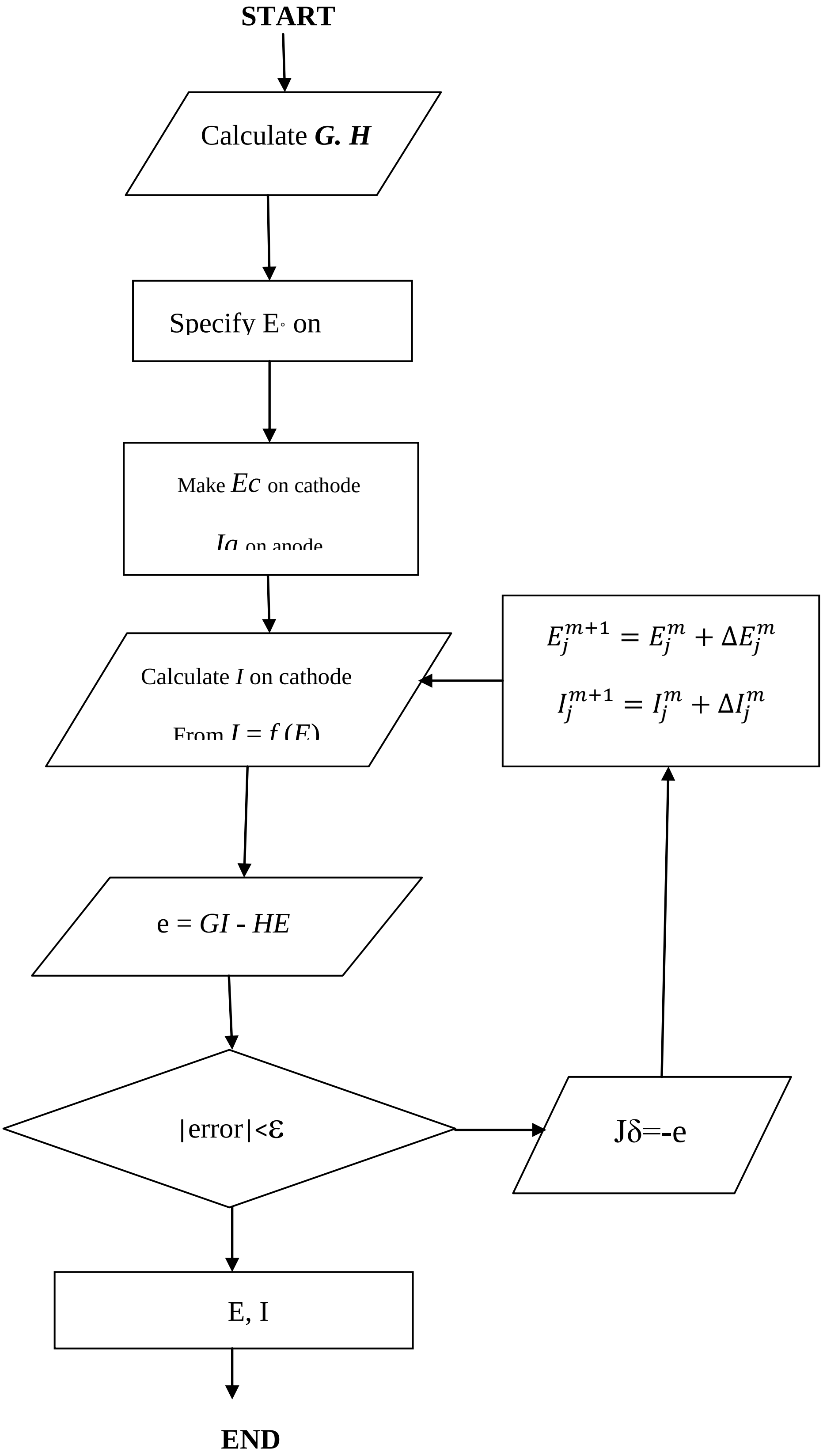

Figure (3-9) Flow chart of the iteration algorithm in solving a cathodic protection problem using BEM. [51].

Chapter Four

Experimental Work

4.1 Introduction

The experimental work deals with modeling of cathodic protection system for buried pipe in soil by impressed current cathodic protection system (ICCPS) technique, which has been built and assembled within a wood soil box in the laboratory. The installation of cathodic protection system was carried out to find the current required and potential to protect a carbon steel pipe segment which is buried inside the soil box in different types of environment and parameters such as soil moisture, pipe coating and anode distance and depth.

The operation of cathodic protection system involved the application of external power from "DC Power Supply" to provide an applied voltage within specific standard required limits, and the resultant current for protection was measured in different specified environments.

4.2 Materials and apparatus

4.2.1 Carbone steel pipe (Cathode)

A segment of (100cm) length, (2.54cm) diameter of carbon steel pipe was used in the present experiment to practice the cathodic protection process, according to the standard ASTM A106. The chemical composition of the pipe compared to the standard specification is illustrated in Table (4-1), and figure (4-1) shows the carbon steel pipe(cathode).

Table (4-1) Chemical composition of the used steel pipe [52].

C%	***Si%***	***Mn%***	***P%***	***S%***	***Cr%***	***Mo%***	***Ni%***	***Cu%***	***V%***	***Fe%***
0.1649	***0.2559***	***0.5027***	***0.0020***	***0.0068***	***0.0251***	***0.0000***	***0.0088***	***0.1505***	***0.0033***	***Rem.***

Figure (4-1) carbon steel pipe (cathode)

4.2.2 Segment of scrap steel pipe (Anode)

The Anode used is scrap steel of 20 cm length, (1.9cm) diameter, which is drilled to connect an isolated electrical wire as shown in Figure (4-2).

Figure (4-2) scrap steel Anode

4.2.3 Power supply

DC power supply type LINI-T, UTP3705 was used to apply voltage as shown in Figure (4-3).

Figure (4-3) DC. Power supply

4.2.4 Reference electrode

Cu/CuSO4 Half Cell Reference Electrode was used for electrochemical measurements, the purpose of using reference electrode is to determine the potential between the carbon steel pipe (cathode) and the environment or the surrounding electrolyte. Figure (4-4) shows the reference electrode.

4.2.5 Soil box

Wooden box was used (no leakage of current was observed) of dimensions (150cm ×62cm ×57cm), filled with soil, pipe (cathode) and anode. Figure (4-4) shows the soil box and reference electrode.

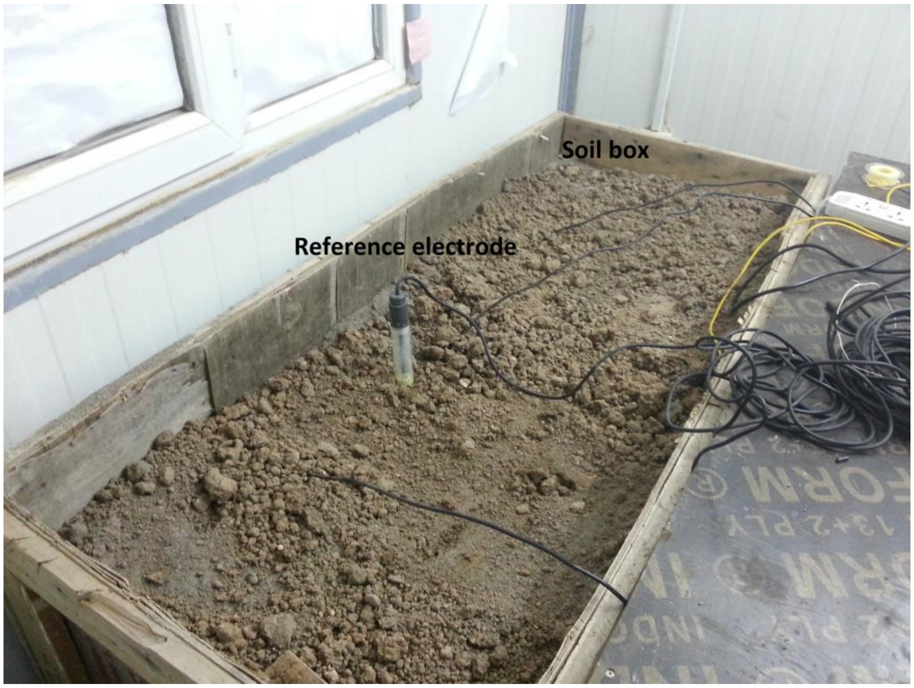

Figure (4-4) soil box and reference electrode

4.2.6 Voltmeter and Ammeter:

An ammeter was used to find the current of the circuit. Two voltmeter wre used; one to measure the potential of the pipe versus the RE, the second was used to measure the voltage between the pipe and the anode. Figure (4-5) shows the voltmeters and the ammeter.

Figure (4-5) Voltmeter and Ammeter

4.3 Soil Resistivity measurement [53]

Winner's four terminal method is the most commonly employed methods in the field measurements. In this method, four contact rods are spaced at equal distance in straight line, and alternating current (AC) is applied between the outer two electrodes. The difference of potential between the line electrodes is observed and the resistivity then calculated from the formula or read directly on the instrument; this is based on the principle of passing an alternating current through the ground between two pins and measuring the volts drop between two other pins placed in between. If the measured resistivity is determined from the formula, it is equal to the resistance (the ratio of the measured voltage divided by the current flowing into the ground) multiplied by the geometric factor (for a Werner array the factor is 2p). The resistivity ρ is then

$$\rho = 2 \times p \times A \times R$$

Where: ρ = resistivity in Ω.cm

A= spacing of electrode, in cm, which represent the depth of burial.

R= resistance, in Ω, Figure (4-6) show the soil resistivity measurements.

Figure (4-6) soil resistivity measurements

4.4 Experimental procedure

4.4.1 Pipe preparation

A pipe of (2.54cm) diameter. Was cut by means of electric cutter into two identical pieces, each of (100cm) length. One piece was bare pipe and another was coated pipe used in cathodic protection rig of the present study. Before we coat the pipe we clean it with emery paper and weld three points of copper wire at the middle and the ends of the pipe by thermite welding, and then coat it with coal tar with tapping (coating efficiency about 85%). The ends of the pipe were closed tightly using rubber stopper and thermal silicon adhesive to prevent the leakage from the environment to the pipe.

4.4.2 Installation of ICCP system

Cathodic protection system was built as shown in Fig. (4-7). Initially bare pipe piece was buried in soil box (with different moisture content, 5, 15 and 60%); electric connections were fixed as shown in Figure (4-7). The anode was installed and buried in many position as shown in Figure (4-8). The reference electrode was placed over the soil surface directly above the buried pipe.

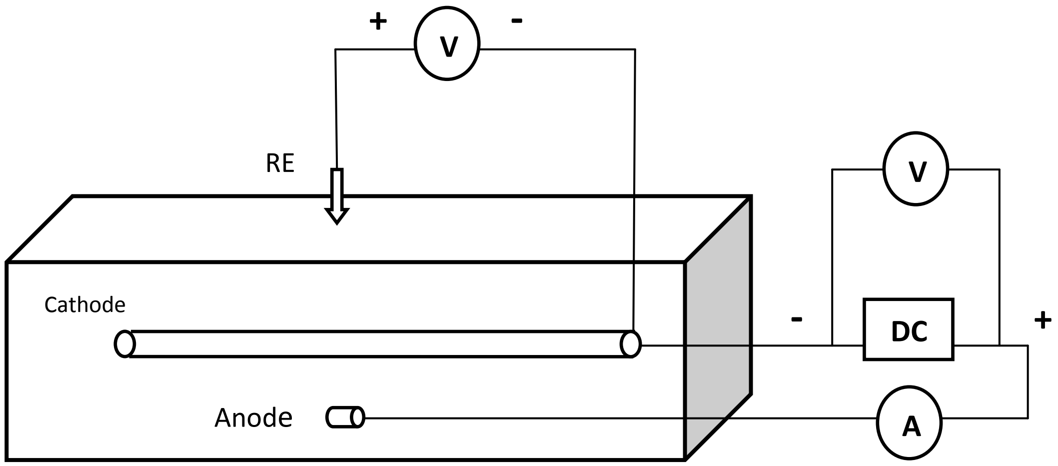

Figure (4-7) Impressed Current Cathodic protection (ICCP) connection

4.4.3 Impressed cathodic protection runs

Before starting operation of the system, native potential to bare pipe was read at each run using copper-copper sulfate reference electrode (CSE) on the electrolyte surface. A DC power supply was employed for voltage application. Applying voltage gradually from 0.1 Volts until we get the proper voltage difference for cathodic protection between the soil and the pipe to be protected. The voltage readings were set to the range of cathodic protection potential (-850 mV to -1100 mV) by varies instruments [53].

The impressed current was recorded at intervals of 1 min over a period of 10 minutes using digital ammeter; also the corresponding supplied voltage was recorded using of digital voltmeter. The off-potential was recorded after 1second of the power supply interrupted by digital voltmeter. The volts apply was supplied in the middle of the carbone steel pipe and taking potential profile of the pipe and electrolyte (soil) along the pipe length every (10cm) that's mean we have (5) potential reading with symmetric way we apply all the above steps on the coated pipe at the same conditions.

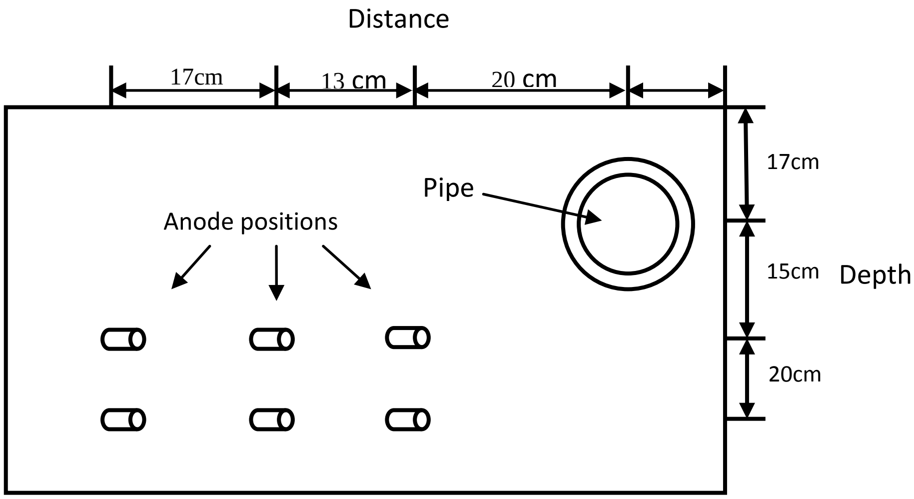

Figure (4-8) Anode position and experiment runs

4.4.4 Potential and Current distribution

Potential and current distribution are plying very important role to verify the efficiency and the power saving in the system.

After fixing the pipe (cathode), the anode should move according to the procedure shown in the Figure (4-8), at a distance of (20, 33, 50) cm and a depth of (15, 35) cm. By taking the first run for example (20cm distance and 15cm depth) etc. every run the potential and the current were recorded in the centre of the pipe also every (10cm) away from the centre of the pipe in the left and right side as shown in the Figure (4-9). The potential was read from the copper/copper sulfate reference electrode (CSE), and the current reading from the ammeter. Figure (4-10) illustrates the current distribution.

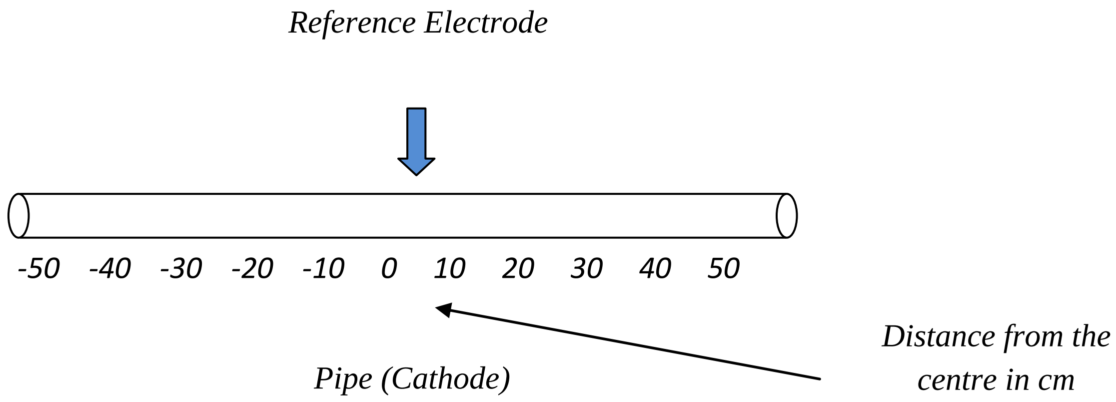

Figure (4-9) Potential distribution runs.

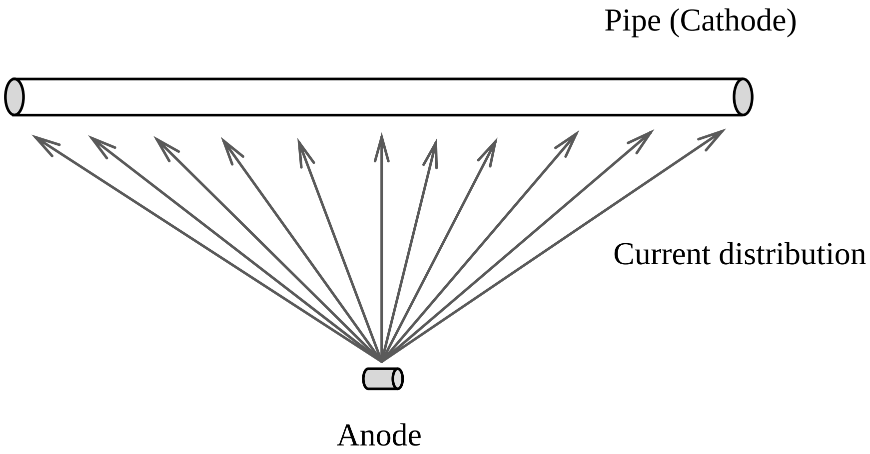

Figure (4-10) Current distribution along the pipe

Chapter Five

Results and Discussion

5.1 Introduction

The experimental results obtained in the present work, one limiting current densities, corrosion potential, protection potential, location of anode and different environment resistivities for bare and coated pipes. Also, these include the effect of location of the anode and cathode for different resistivities, current and voltage calculation in order to evaluate models which represent these conditions for bare and coated pipe with statistical methods. The effects of various variables on experimental results are stated.

5.2 The effect of cathodic protection parameters:

Cathodic protection is an effective electrochemical technique for preventing corrosion of metallic structures. It has widespread applications on various structures, suffering serious problems of corrosion in the environments. The main problem with this protection method is to determine the parameters (current density and potential)

5.2.1 The effect of Anode position on:

5.2.1.1 Voltage required to system.

Figures (5-1) to (5-4) show the effect of anode positions (distance and depth) to cathode (pipe), bare and coated on voltage required to achieves cathodic protection potential (-0.85V). It has been noticed that the voltage required directly affected by the anode position due to increasing in soil resistivity whenever the distance increase. Also the consumption of power in moist soil is less than dry soil due to the soil resistivity in dry soil is higher than moist soil so the current drainage in the moist soil is higher than dry soil.

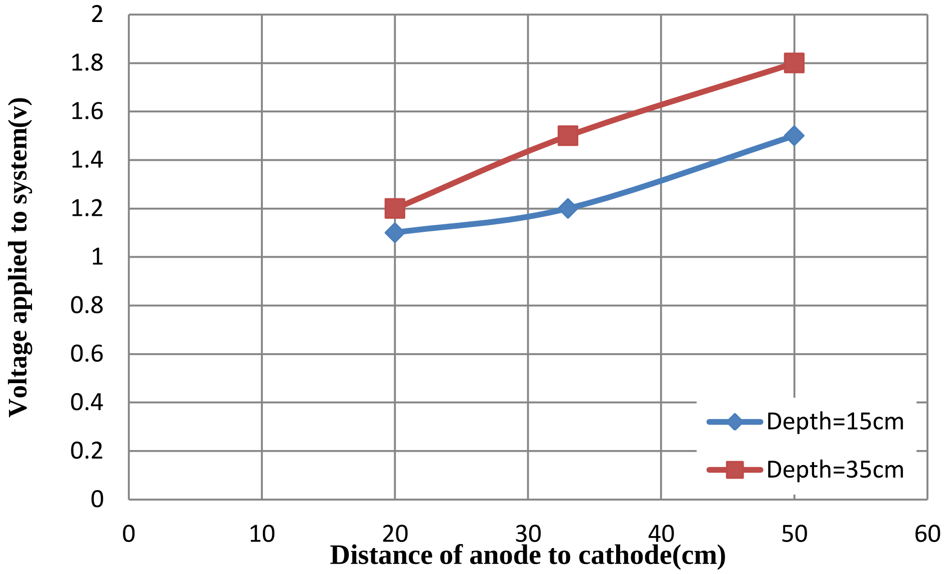

Figure (5-1) the effect of anode position on the voltages applied to get cathodic protection potential (-0.85v) in bare pipe, moisture environment (60%).

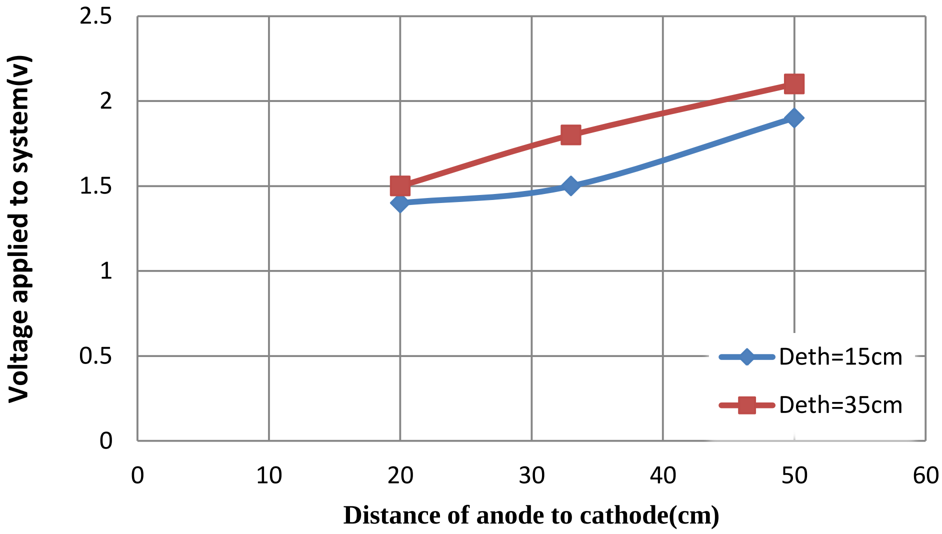

Figure (5-2) the effect of anode position on the voltages applied to get cathodic protection potential (-0.85v) in bare pipe, dry environment (5%).

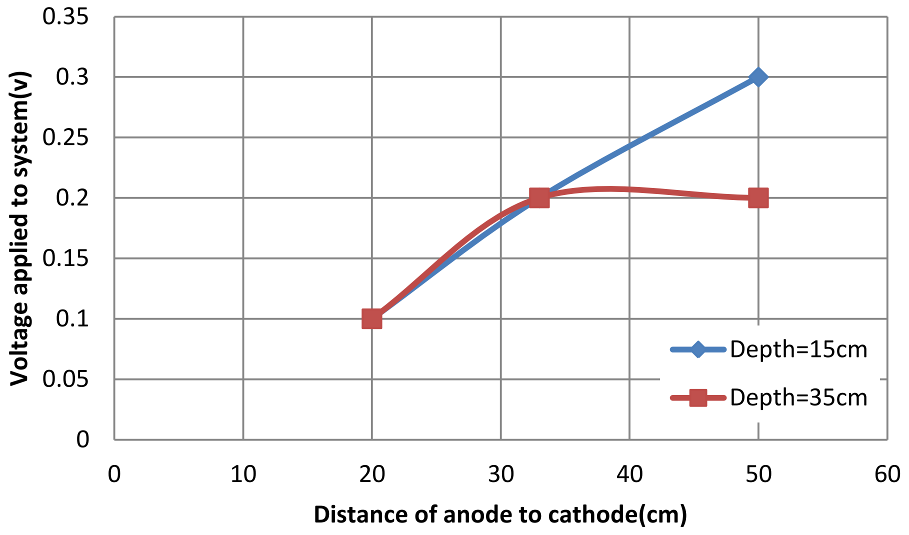

Figure (5-3) the effect of anode position on the voltages applied to get cathodic protection potential (-0.85v) in coated pipe, moisture environment (60%).

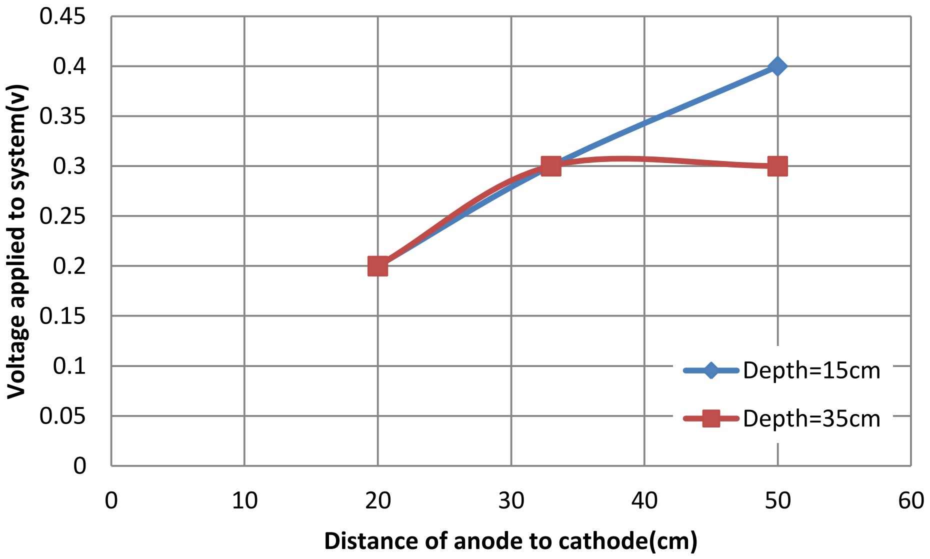

Figure (5-4) the effect of anode position on the voltages applied to get cathodic protection potential (-0.85v) in coated pipe, dry environment (5%).

5.2.1.2 The Required Current Density.

The current density requirement is defined as the amount of the protective current needed per unit area to achieve full cathodic protection to the pipe surface. This parameter is dependent on parameters such as coating type and thickness, number of coating defects, and age of coating [54]. The distribution of the current (that flow from anode), to the surface area of the cathode (pipe) is highly effected by the distance between cathode and anode. Increasing distance between anode and cathode awarded better distribution of the current on the surface area of the cathode and so the more protection will be achieved. Cathodic protection current density is more uniform with increasing distance between cathode (pipe) and anode. That is because increasing the distance between anode and cathode increases the distribution of current density on the pipe, i.e. increasing the protective surface area of the pipe (cathode).

Figures (5-5) to (5-8) illustrate the effect on current distribution along the pipe of (100cm). Anode was moved along the y-axis to change the distance between the pipe and the anode. It means that, the anode was changed only on one direction; x-coordinate and z-coordinate were kept without changing. However, for each anode distance, the distribution was not uniform over the outer surface of the pipe, i.e. very significant peak as shown and observed with decreasing in the distance between the pipe and the anode. For instance, at a distance of 20 cm (decrease the soil resistance), charge density increases near the pipe surface at the point facing the anode, because the charges reach the pipe more quickly than the rest of the pipe surface. Charges have to cover large distance to reach. It means that with decreasing distance between the anode and the pipe, the conductivity resistance is decreased and surface kinetics plays an important role in the charge transfer reaction.

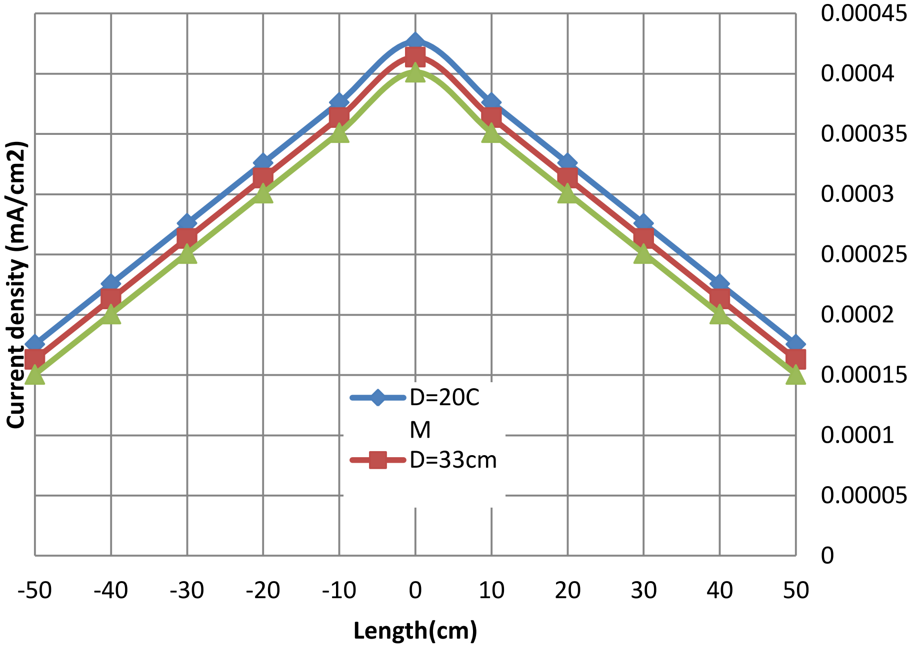

Figure (5-5) Current distribution along the bare pipe of moisted soil (60%) and 15cm depth, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

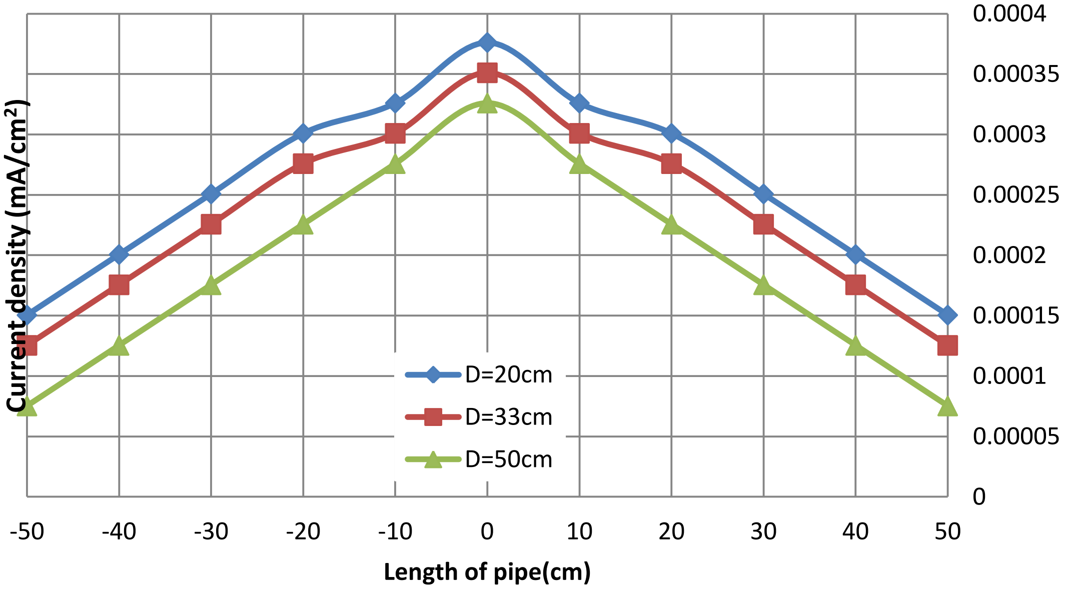

Figure (5-6) Current distribution along the bare pipe of moisted soil (60%) and 35cm depth, where D= Anode distance to cathode ,resistivity (1000 ohm.cm)

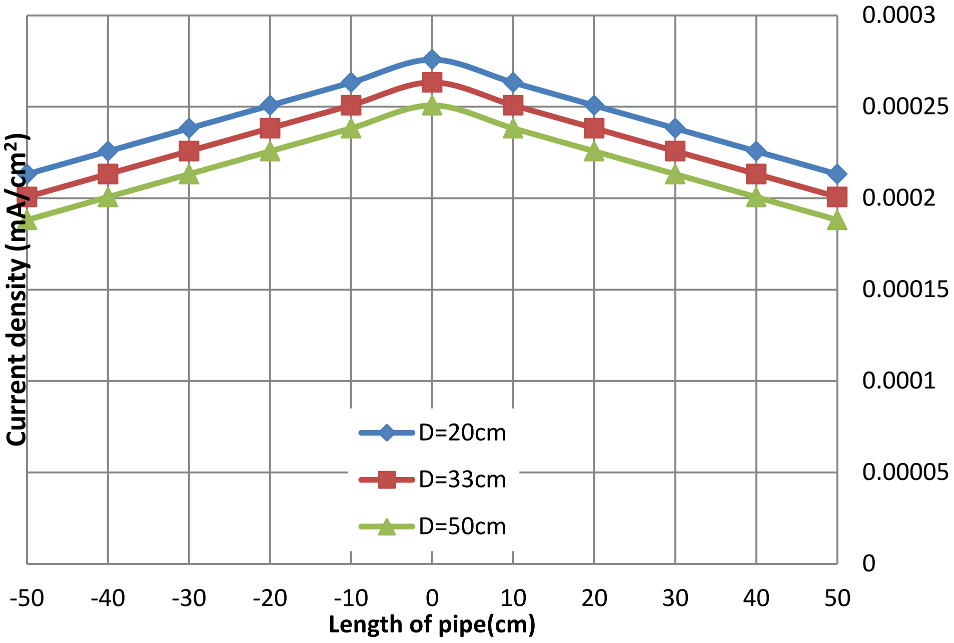

Figure (5-7) Current distribution along the bare pipe of dry soil (5%) and 15cm depth, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

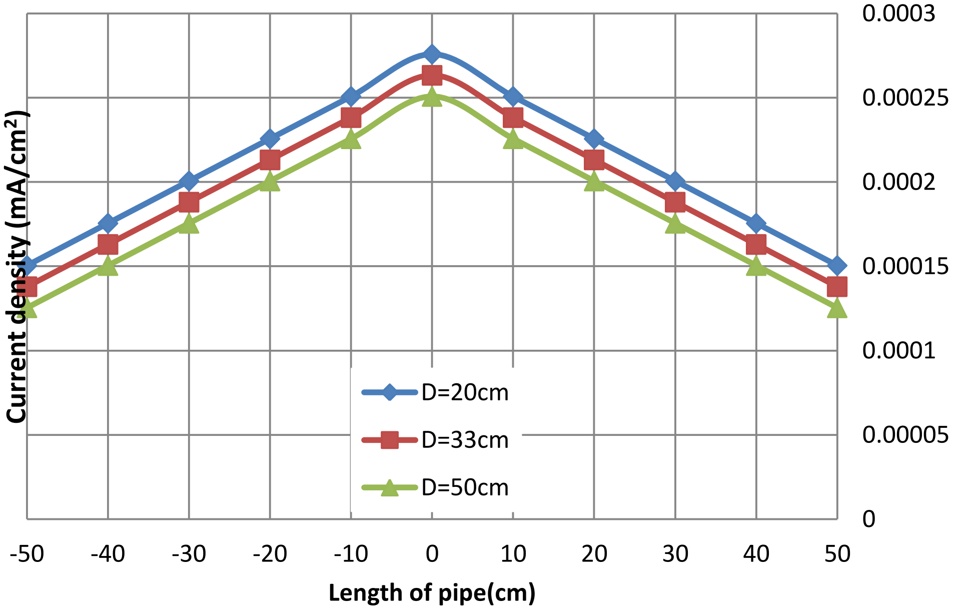

Figure (5-8) Current distribution along the bare pipe of dry soil (5%) and 35cm depth, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

Saving in power means, the value of the current enters the structure equals the current leaves the structure, i.e. there is no forfeited in the current. The power saved as a function of anode to pipe distance is shown in Figure (5-9). It is very obvious that the anode at a distance of 33cm and depth of 35cm in moisted and dry soil is saving the maximum amount of power, due to the uniform distribution of current along the pipe, i.e. protection is achieved within the optimum values. Saving in power which has been calculated in case of 20cm anode distance and 15cm depth was also observed to be low. The case of anode at a distance of 50cm and 35cm depth away from the buried pipeline gives the lowest value of powered saved due to the loss of the given current into the soil. The phenomenon of stray current might be observed here.

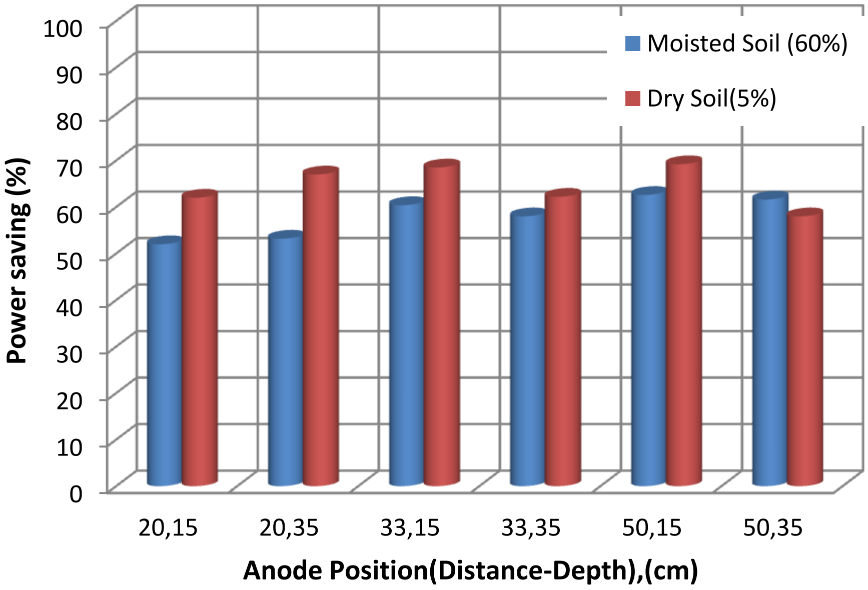

Figure (5-9) Comparison of power saving for several anode positions, resistivity (1000 ohm.cm).

5.2.1.3 Potential between cathode and soil

The distance between anode and cathode play very important role especially on voltages applied and potential between cathode and soil via copper-copper sulfate electrode (CSE), when the anode distance increase the potential decrease. As shown in figure (5-10) and (5-11) the data collected at a fixed voltage applied (1.0 Volt).

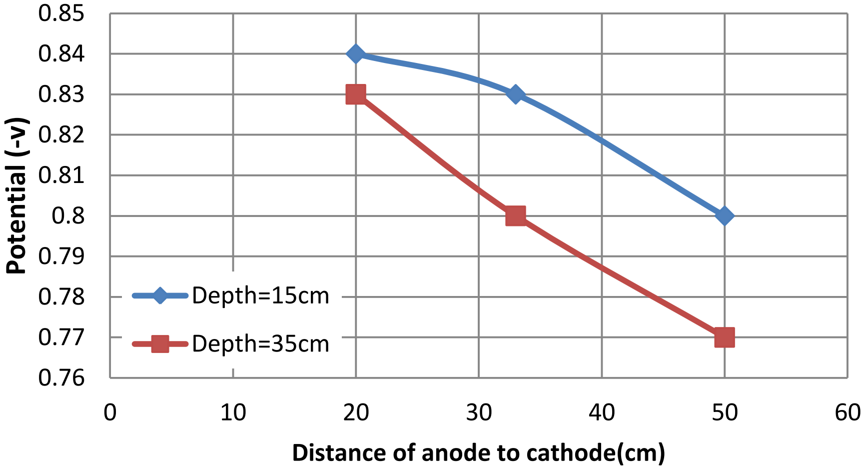

Figure (5-10) the effect of anode distance on potential of bare pipe, moisture environment (60%) at fixed 1.0 volt applied, resistivity (1000 ohm.cm)..

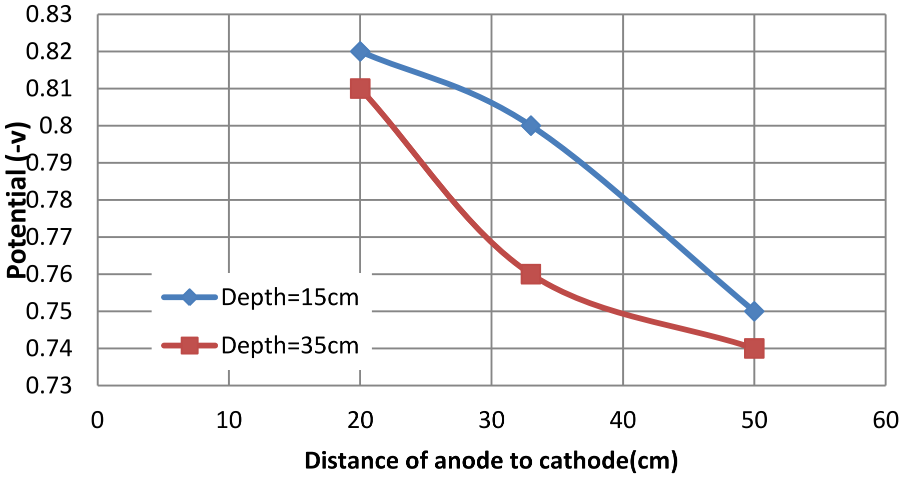

Figure (5-11) the effect of anode distance on potential of bare pipe, dry environment (5%) at fixed 1.0 volt applied, resistivity (1000 ohm.cm).

In order to calculate the power required to achieve the protection, it is necessary to discuss the potential distribution along the pipe, the resistance to charge transfer across the interface increases at the point on the pipe facing the anode due to which surface kinetics controls at this point. The electrons on metal side of the interface will not be consumed readily, at the surface, due to high resistance at the interface and as a result potential is dropped at this point. While, on the other hand, all electrons near the edges, where resistance is low, are consumed immediately and, as a result, potential rises near the edges. It is noticeable also the nearest anode to the cathode has more potential than the Furthest anode due to soil resistivity increase with increasing distance of anode. Figures (5-12) to (5-15) show the potential distribution via (CSE) along the bare pipe in different anode position and environments at a fixed 1.1 Volt. These figures also show that the potential profile is increasing with the move away from the source of voltage applied.

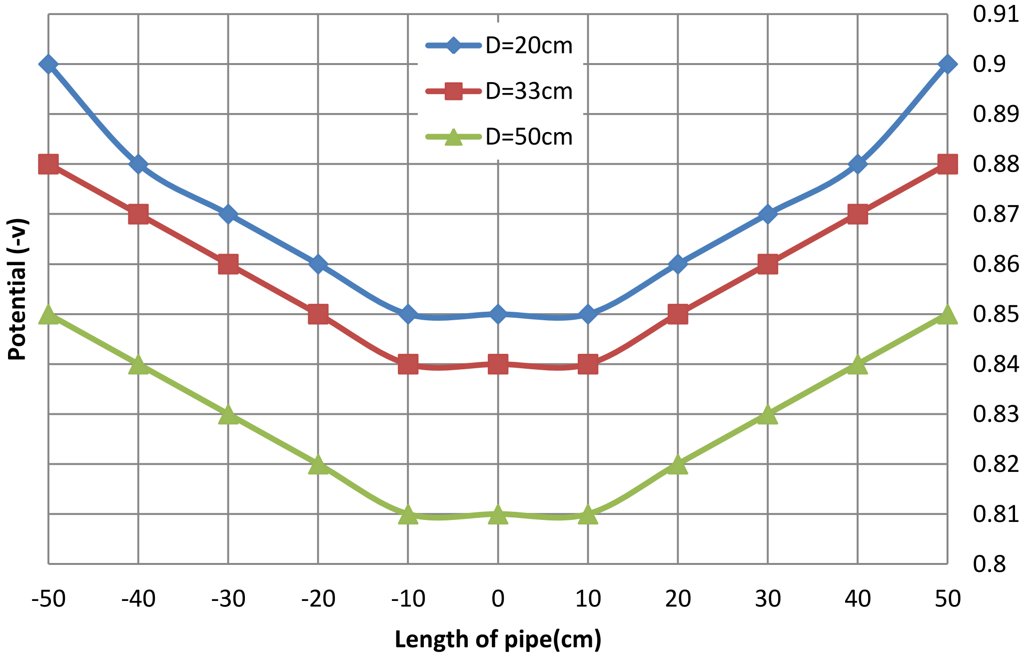

Figure (5-12) the distribution of potential along the bare pipe, moisture environment (60%) and 15cm depth at fixed 1.1 volt applied, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

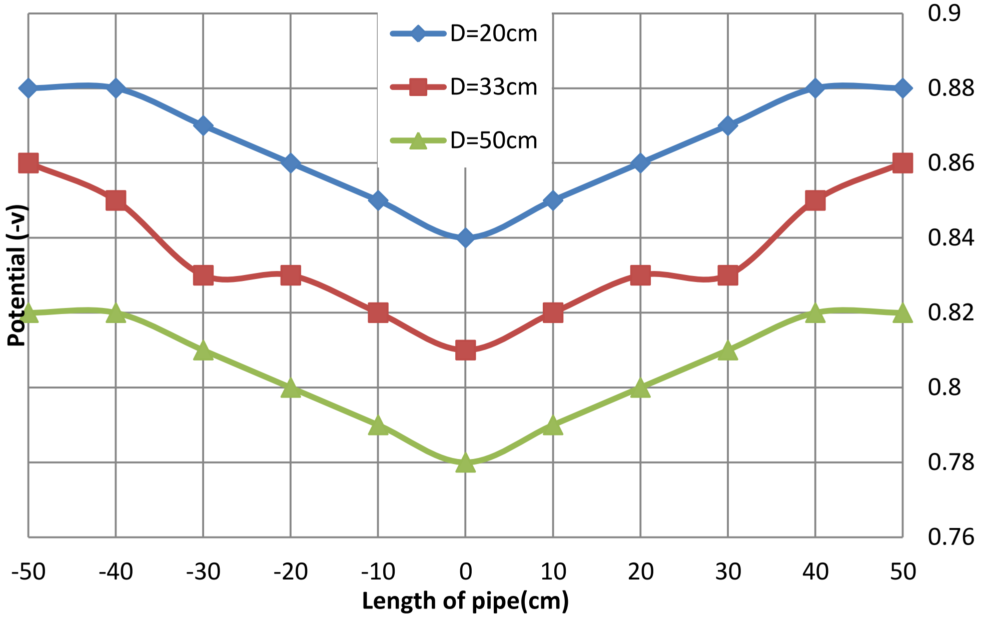

Figure (5-13) the distribution of potential along the bare pipe, moisture (60%) environment and 35cm depth at fixed 1.1 volt applied, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

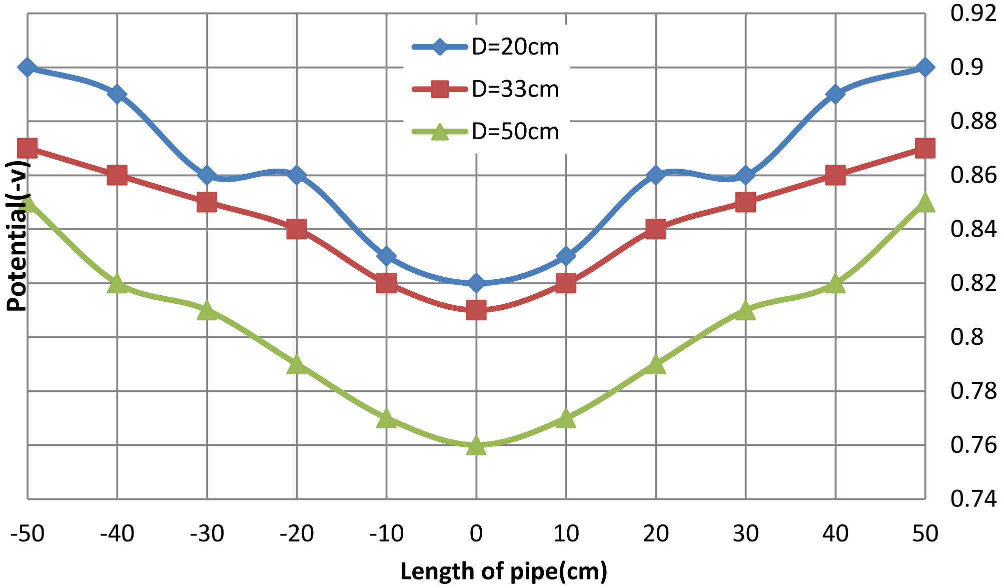

Figure (5-14) the distribution of potential along the bare pipe, dry environment (5%) and 15cm depth at fixed 1.1 volt applied, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

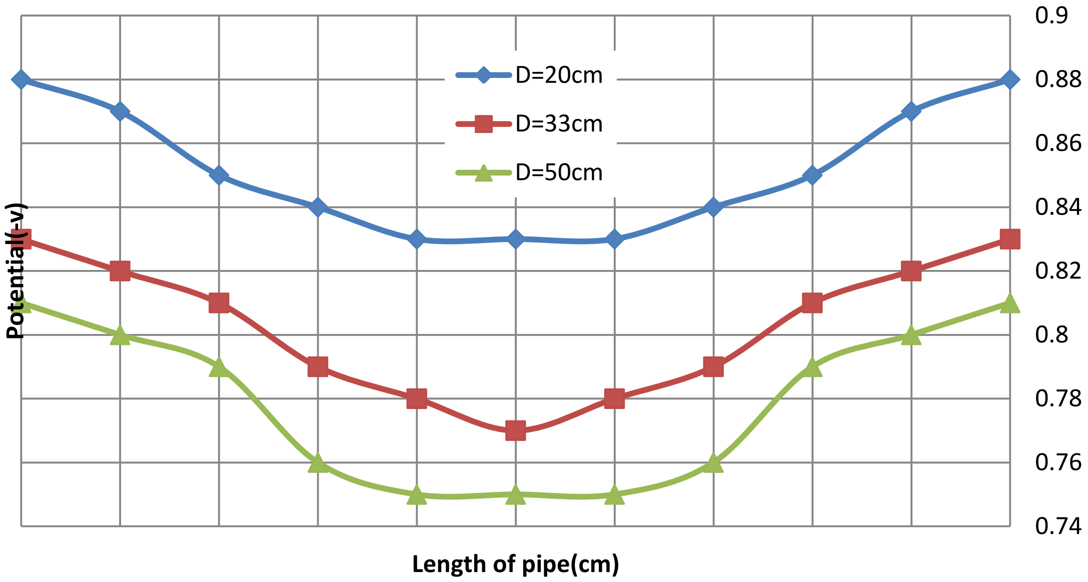

Figure (5-15) the distribution of potential along the bare pipe, dry environment (5%) and 35cm depth at fixed 1.1 volt applied, where D= Anode distance to cathode, resistivity (1000 ohm.cm).

5.2.2 Effect of soil moisture content

Soil moisture content is the amount of water in an unsaturated soil, expressed as a volume of water per unit volume of porous media, or as a mass of water per unit oven-dry mass of soil. Depending on the amount of water in soil it’s varying in winter and summer. From the experimental results taking three values of water content in soil (5, 15, 60) %, the relationship of soil moisture content directly proportional to the current density from the anode towards the cathode (structure to be protected). As the moisture content of soil increased, the cathodic protection current density increased too due to interior waters accelerate electrochemical current that passing through soil and complete the electric circuit in the CP system as shown in Figure (5-16).

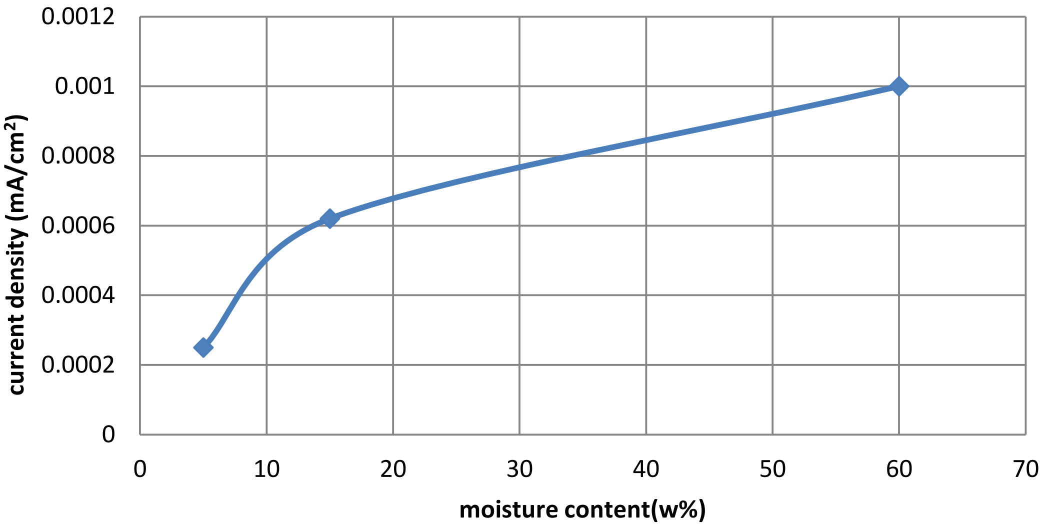

Figure (5-16) effect of soil moisture content on current density.

5.2.3 Effect of soil resistivity

As is well known the relationship between soil moisture content and soil resistivity is an inverse relationship. That means when the soil moisture content increase the resistivity of soil decrease, that's lead to when the soil resistivity increase (750,1000,1500) Ohm.cm the current density decrease as shown in Figure (5-17).

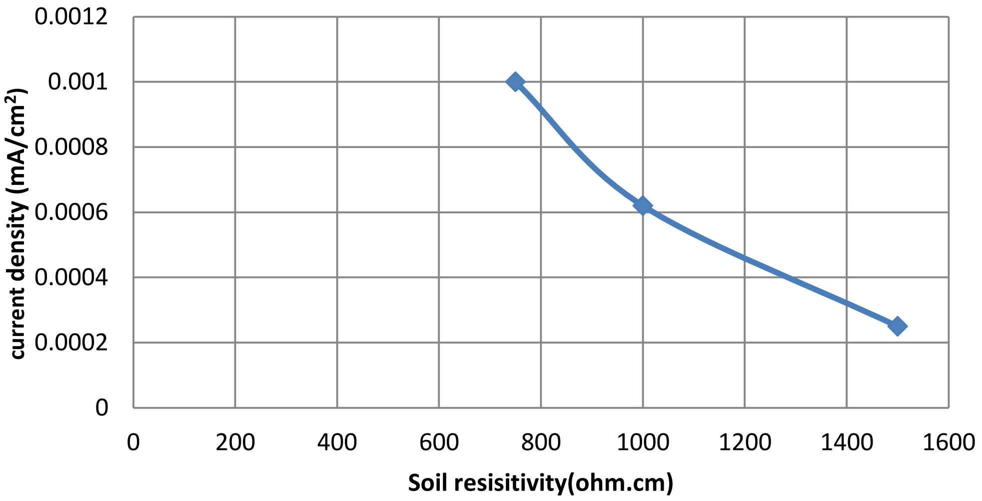

Figure (5-17) effect of resistivity on current density.

Table (5-1) correlates resistivity values with degree of corrosivity. The interpretation of soil resistivity varies among corrosion engineers. However, Table (5-1) is a generally accepted guide, while Table (5-2) correlates the effect of chloride on corrosion of buried steel pipelines.

Table (5-1) Soil resistivity versus degree of corrosivity [55].

Soil resistivity, Ohm.cm	Degree of corrosivity
0 – 500	Very corrosive
500 – 1,000	Corrosive
1,000 – 2,000	Moderately corrosive
2,000 – 10,000	Mild corrosive
Above 10,000	negligible

Table (5-2), Effect of chloride on corrosion of buried steel pipelines [55].

Chloride concentration, ppm	Degree of corrosivity
> 5,000	Sever
1,500 – 5,000	Considerable
500 – 1,500	Corrosive
< 500	Threshold

5.2.4 Paint and Coating effect

The most effective method of mitigation corrosion on the external surface of buried pipeline is a protective coating, supplemented with cathodic protection systems. The performance of any particular coating system is directly related to the conditions encountered during the installation and operation life of the pipeline facility [56].

Figures (5-18) and (5-19) show the relationship between the voltages applied to system and the current density in bare and coated pipes at different environments. The comparison between two the Figures illustrates that bare pipe needs more applied voltages to achieve the optimum current density for protection than the coated pipe, that mean we need more power to get protection. In each Figures (5-18) and (5-19) the environments play important role that is the moisture environment give the system more current than dry environment.

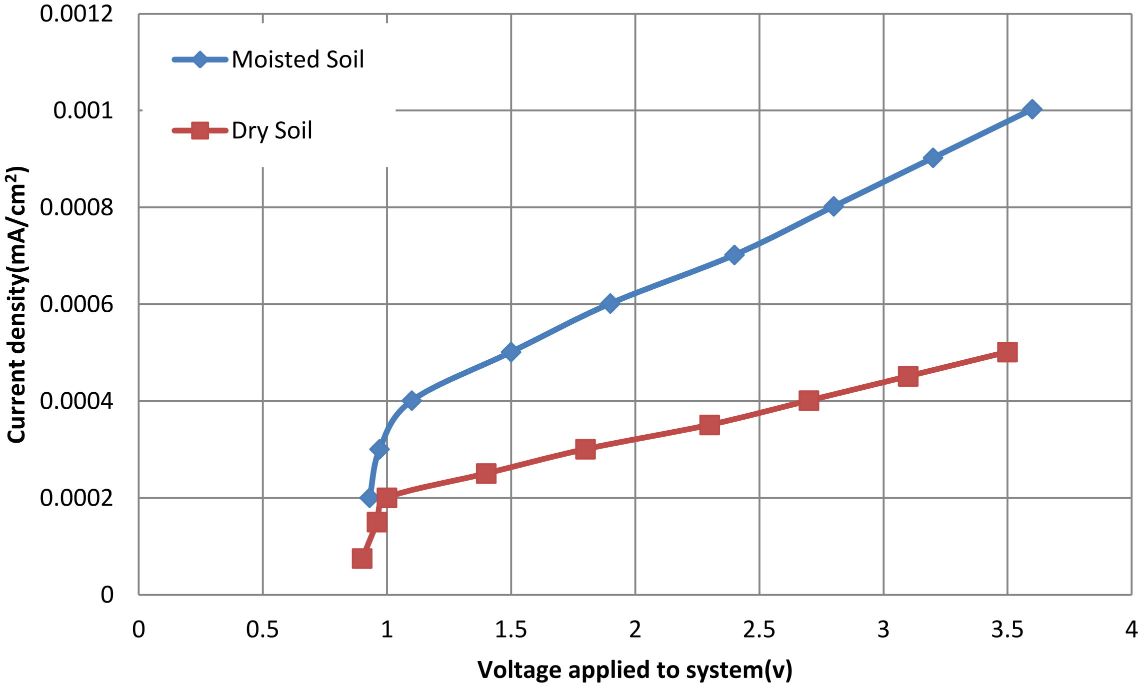

Figure (5-18) bare pipe at a distance of 20cm and depth of 15cm, resistivity (1000 ohm.cm).

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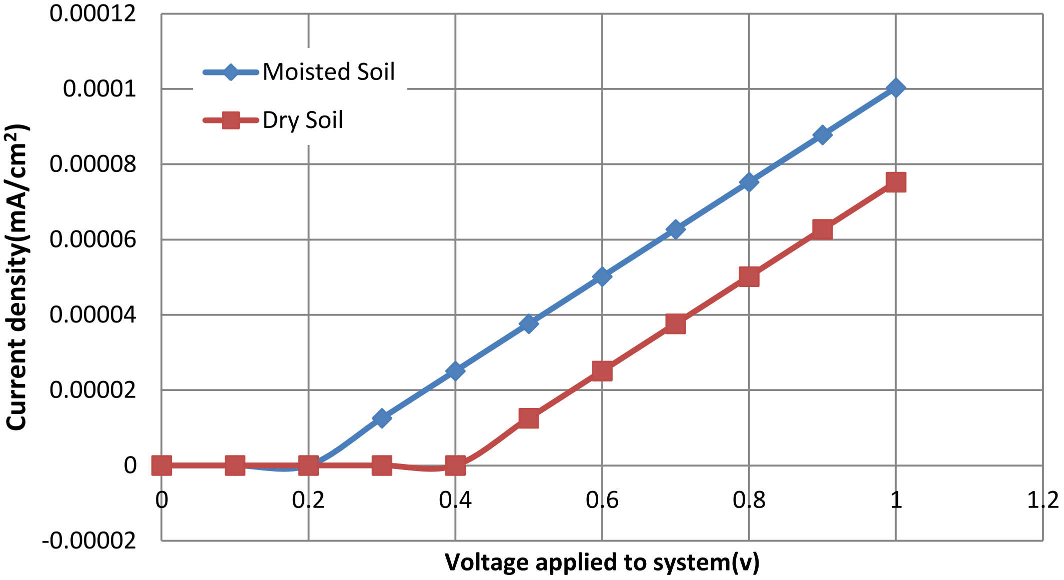

Figure (5-19) coated pipe at depth of 15cm, resistivity (1000 ohm.cm).

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The isolation effect plays very important role that's where the coated pipeline saving more power than the un-coated pipeline, for example in Figure (5-20) at the anode distance (50cm) in moisture environment across coated and bare pipe, the bare pipe spend much power than coated pipe.

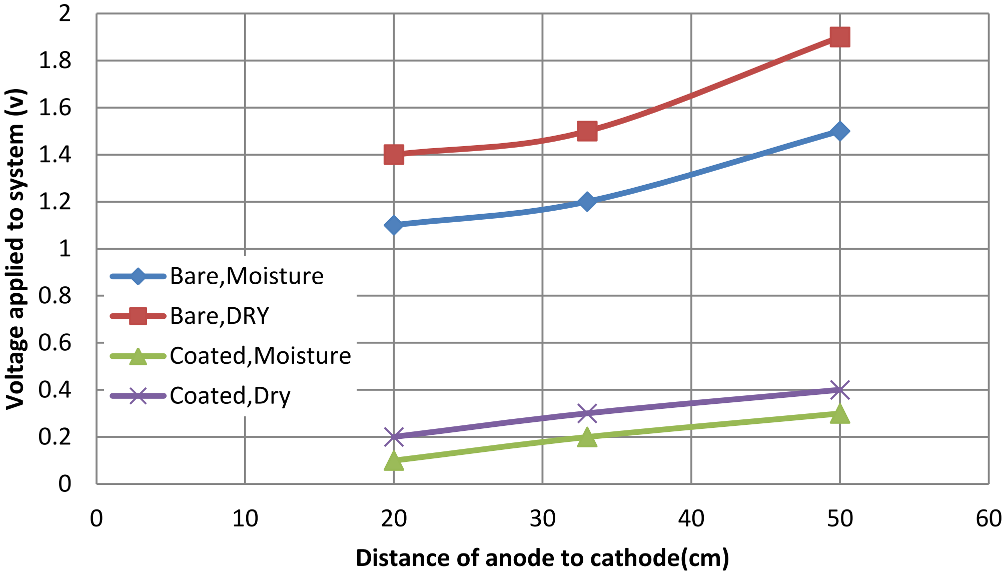

Figure (5-20) the effect isolation on the voltages applied on a pipe with 15cm depth, resistivity (1000 ohm.cm), to achieve cathodic protection potential (-0.85V).

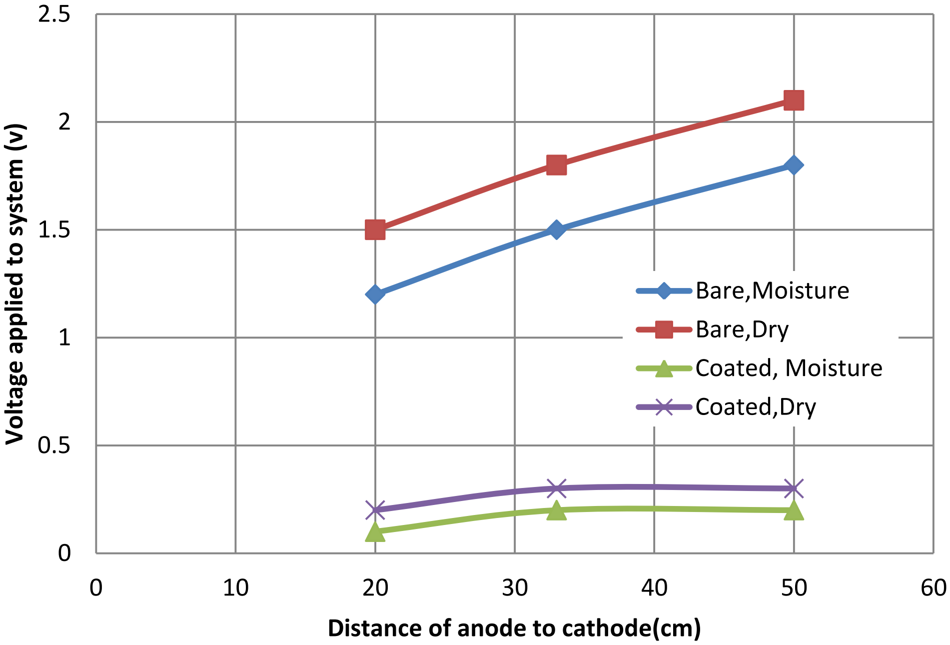

Figure (5-21) the effect isolation on the voltages applied on a pipe with 35cm depth, resistivity (1000 ohm.cm), to achieve cathodic protection potential (-0.85V)

The value of the current density is dependent on the quality of the coating used. The technique used for laying the pipes into the ground, types and dimensions of the pipes, environmental conditions (temperature, pH, etc.) and any measures taken to detect and repair coating damages [57].

Additionally, the preparation and coating of pipeline joints was a significant effect on the current density demand and coating defects are frequently found in such areas. Provided the coating on the pipeline, initially has relatively few defects, the current density required will be relatively low to begin with time, the coating will undergo normal ageing and the current density requirement is expected to gradually increase.

5.2.5 The Effect of Anode to Cathode Surface Area Ratio

The relative size of the anode to cathode areas is a factor in determining the amount of corrosion damage. If the anode area is large (low anode current density) and the cathode area is small, the total current may be negligible because of the passivity and other interfering affects at the cathode surface and the consequent small damage to the anode area is not important because it is distributed over an appreciable area. On the other hand, if the anode area is small (high anode current density) with respect to the cathode area, the corrosive action is localized and severe local damage may result. Logan, Rogers, and Putman [58] studied this factor and they found for a given potential difference Figure (5-22) explain this point.

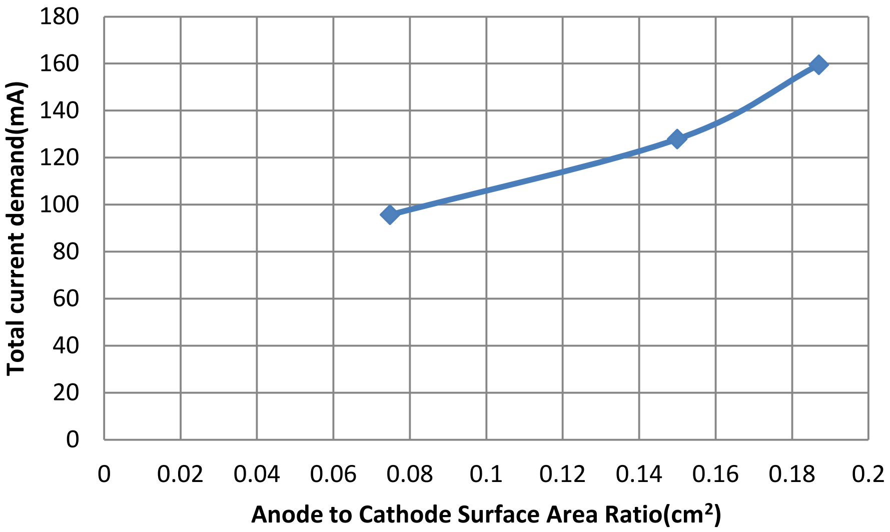

Figure (5-22) the effect of anode to cathode surface area ratio to the total current demand, resistivity (1000 ohm.cm).

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5.2.6 Polarization Curve

A family of dynamic polarization curves are chosen to model the effect of polarization behavior. The polarization techniques measurements were implemented based on two methodologies as follows:

- Polarization measurements to study the behavior of pipe samples, i.e. corrosion rate, pipe to soil potential …etc.
- Polarization curves for both cathode and anode, based on electrochemical principles, were obtained from experimental data and used as a reference to study the effect of soil resistivity (conductivity) on the design of the cathodic protection system. Figures (5-23) to (5-28) show the polarization curve of cathodic protection in different run with different parameters.

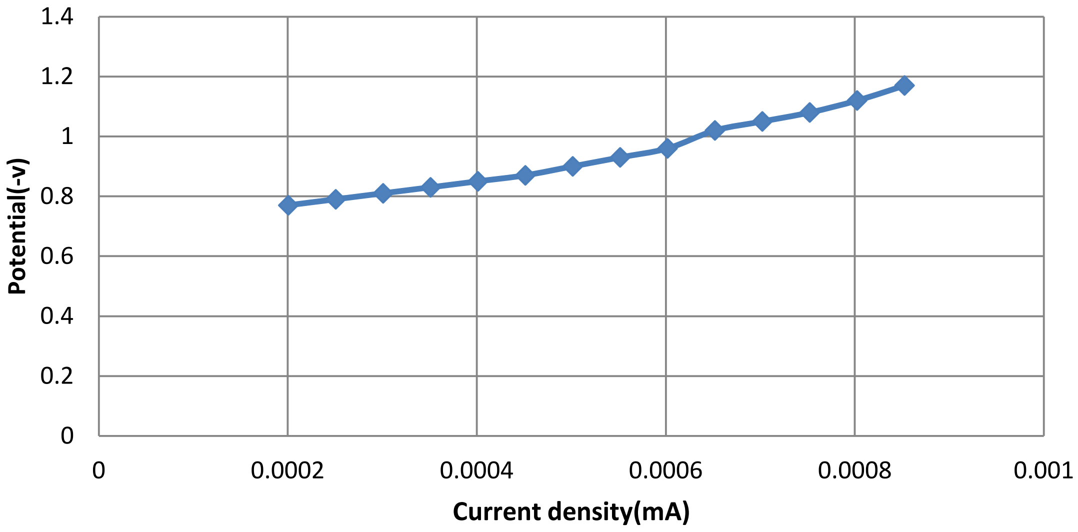


Figure (5-23) polarization curve of bare pipe, moisture environment (60%) at a distance of 20cm and depth of 15cm, resistivity (1000 ohm.cm).

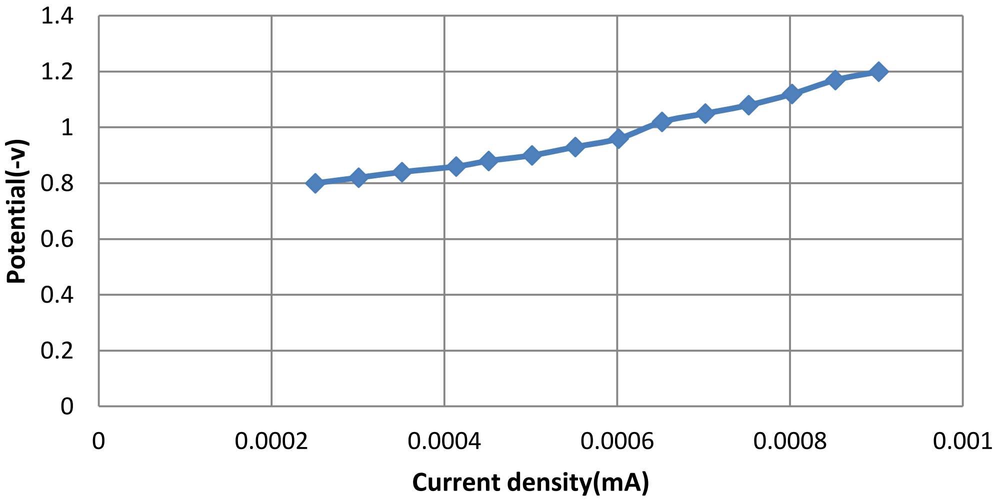
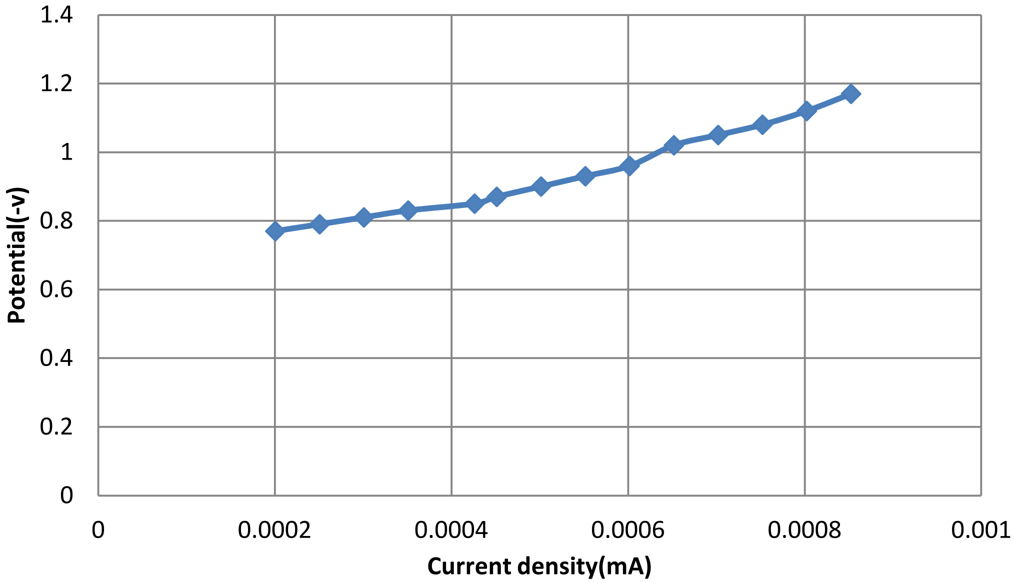
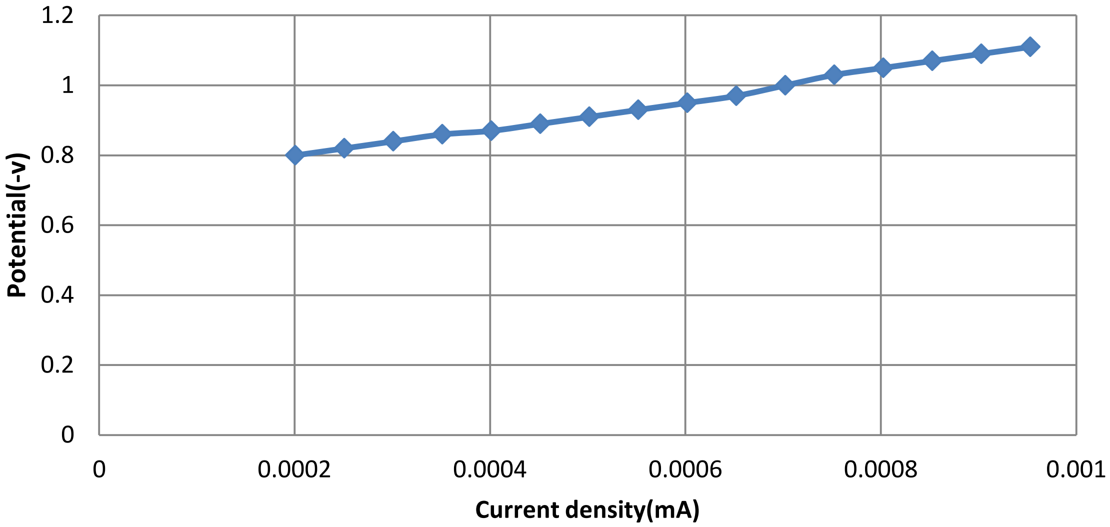


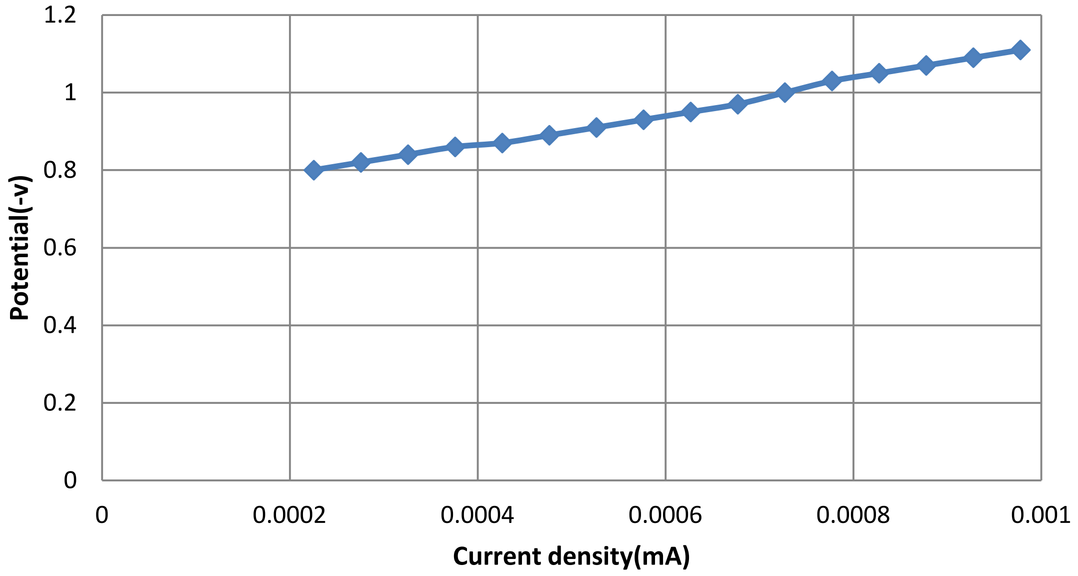
Figure (5-24) polarization curve of bare pipe, moisture environment (60%) at a distance of 33cm and depth of 15cm, resistivity (1000 ohm.cm).



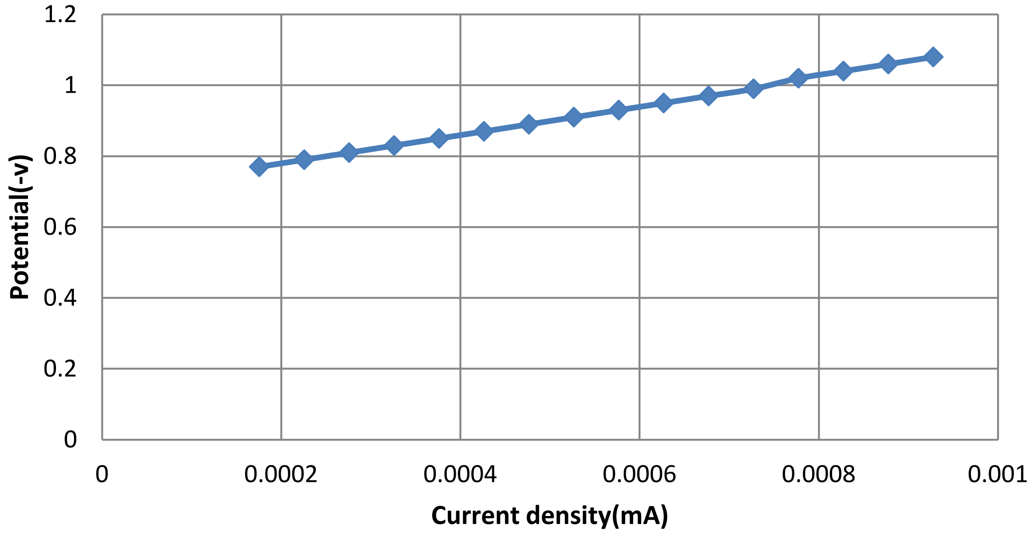
(5-25) polarization curve of bare pipe, moisture environment (60%) at a distance of 50cm and depth of 15cm, resistivity (1000 ohm.cm).



(5-26) polarization curve of bare pipe, dry environment (5%) at a distance of 20cm and depth of 35cm, resistivity (1000 ohm.cm).



(5-27) polarization curve of bare pipe, dry environment (5%) at a distance of 33cm and depth of 35cm resistivity (1000 ohm.cm).



(5-28) polarization curve of bare pipe, dry environment (5%) at a distance of 50cm and depth of 35cm, resistivity (1000 ohm.cm).

5.3 Power consumption and saving of the system

It is necessary to calculate the power needed (consumed) to implement this system in reality. Like the way of calculating electrical power, cathodic protection power is calculated by multiplying the total current by the applied potential as per equation (5-1). It is important to emphasize that the applied potential is constant, so the main effective factor is the total current. This value will be produced based on the calculations of the software. [59].

$$CP_{power} = I \times V \qquad \dots (5\text{-}1)$$

Where:

CP_{power} = Cathodic protection power in (Watts)

I = Total Current (A)

V = Applied potential in (V)

Figures (5-29) to (5-32) illustrates the power consumed and saved for rectifier (power supply), in different anode position and environments.

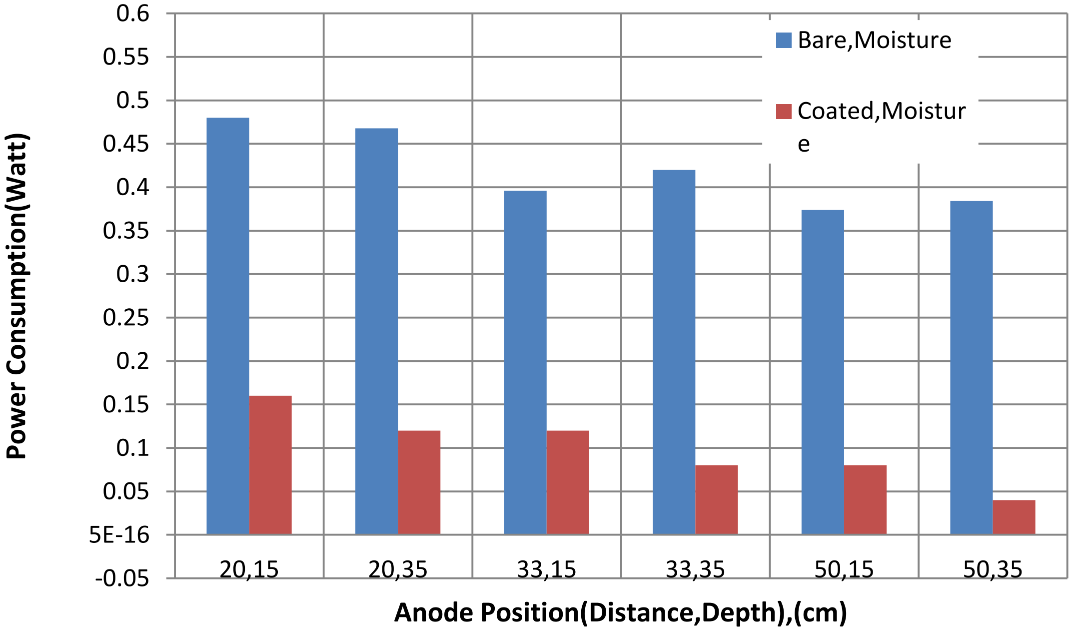


Figure (5-29) power consumption of bare pipe and moist soil (60%) in different anode position.

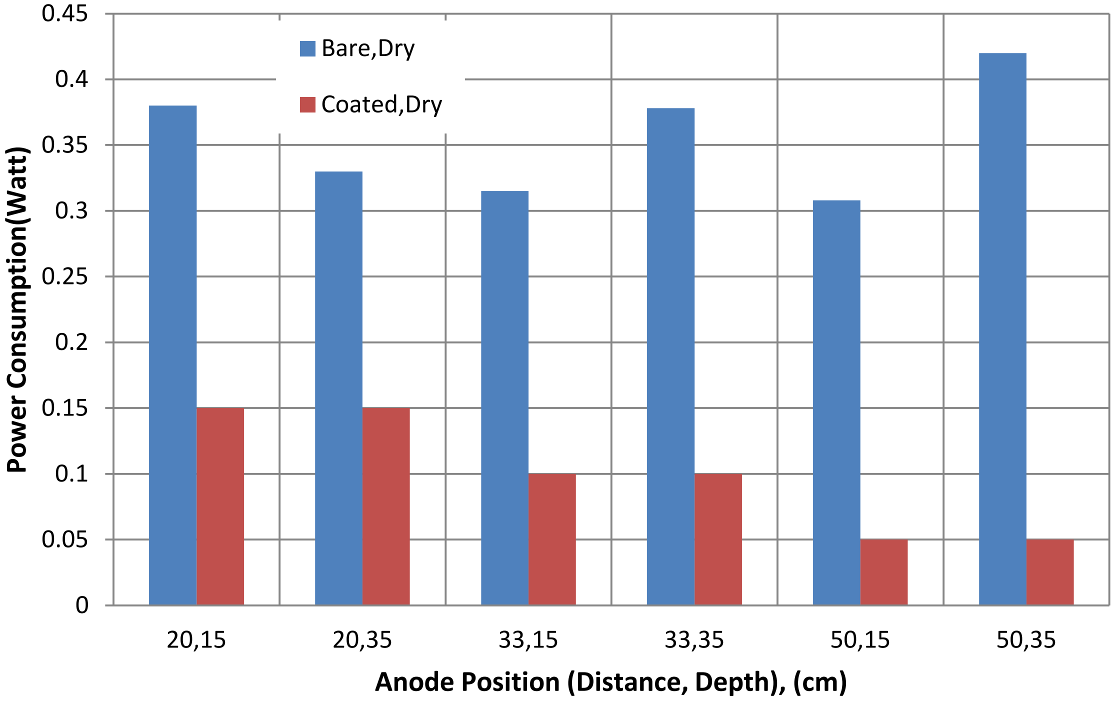


Figure (5-30) power consumption of bare pipe and dry (5%) soil in different anode position.

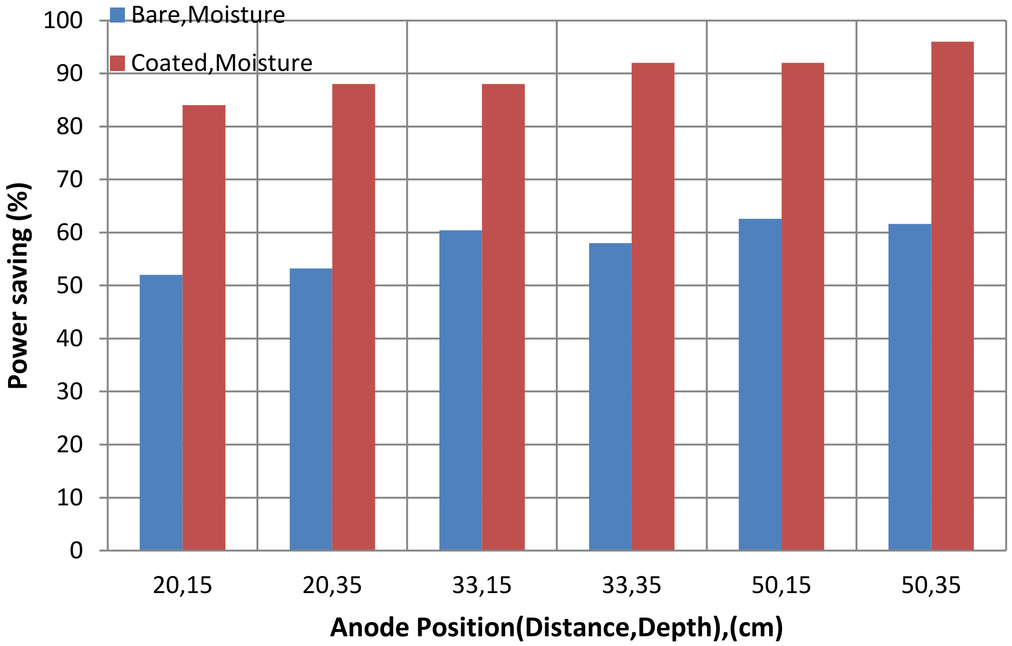


Figure (5-31) power saving of bare pipe and moist soil (60%) in different anode position.

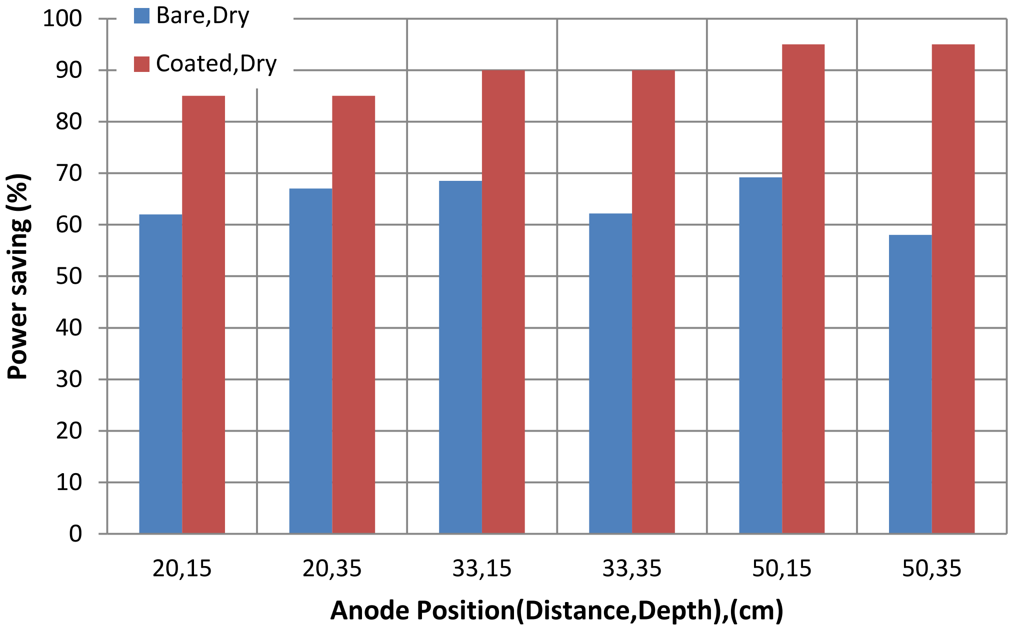


Figure (5-32) power saving of bare pipe and dry (5%) soil in different anode position.

5.4 Cathodic protection correlation

By using regression techniques to achieve mathematical correlation describing the potential for cathodic protection based on 647 runs each for coated and uncoated pipe that taken to cover all parameters affecting cathodic protection as shown in equation below.

$$\xi = \beta_\circ + \beta_1 V + \beta_2 I + \beta_3 D + \beta_4 Dp + \beta_5 m \qquad \ldots (5\text{-}2)$$

There are several factors affecting the cathodic protection and every factor has a special effect in terms of impact strength. We apply the above equation with the mathematic model on access to ranges of cathodic protection potentials limit.

Consider:

ξ= Cathodic protection potential between (-0.85 to -1.1) volts.

V=Voltage applied to achieve cathodic protection potential rang of (-0.85 to -1.1) volts, (volt).

I= current required to achieve cathodic protection potential rang of (-0.85 to 1.1) volts, (mA).

D= Distance of anode to cathode, (cm).

Dp= Depth of anode from cathode, (cm).

m= Environment (soil), moisture, (%).

$\beta_\circ$, β_1, β_2= unknown parameters.

Collecting data from experimental results of bare and coated pipe applying it in equation (5-2), resistivity (1000 ohm.cm).,at any soil moisturethat will be obtain:

1. Bare Carbon steel pipe.

$$\xi = 0.791+0.091\,V+0.144\,I-0.00188\,D-0.00180\,Dp-0.00537\,m \qquad \text{… (5-2a)}$$

Correlation between each factors can be get as shown in Table (5-3).

Table (5-3) Correlation between factors affecting cathodic protection of bare pipe.

	Potential(ξ)	*Voltage applied(V)*	*Current(I)*	*Distance(D)*	*Depth (Dp)*	*Environment(m)*
Potential(ξ)	1	0.852027938	0.6556568	-0.01731711	0.00257404	-0.032360465
Voltage applied(V)	0.852027938	1	0.5199678	0.30833687	0.209030672	-0.201146527
Current(I)	0.655656795	0.519967798	1	0.01188551	0.14330017	0.669487372
Distance(D)	-0.017317109	0.308336865	0.0118855	1	-0.06320461	-0.030707291
Depth(Dp)	0.00257404	0.209030672	0.1433002	-0.06320461	1	0.114929852
Environment(m)	-0.032360465	-0.201146527	0.6694874	-0.03070729	0.114929852	1

2. Coated Carbon steel pipe.

$$\xi = 0.467+0.742\,V -1.675\,I +0.00057\,D -0.00067\,Dp +0.2299\,m \qquad \ldots (5\text{-}2b)$$

Correlation between each factors can be get as shown in Table (5-4).

Table (5-4) Correlation between factors affecting cathodic protection of coated pipe.

	Potential(ξ)	*Voltage applied(V)*	*Current(I)*	*Distance(D)*	*Depth(Dp)*	*Environment(m)*
Potential(ξ)	1	0.901689938	0.866724971	-0.05499659	0.012378404	0.283031592
Voltage applied(V)	0.901689938	1	0.789097253	9.8232E-18	-3.01662E-18	-0.132067636
Current(I)	0.866724971	0.789097253	1	0.36229743	-0.220870514	0.332738772
Distance(D)	-0.05499659	9.82318E-18	0.362297431	1	-1.18655E-17	2.70472E-17
Depth(Dp)	0.012378404	-3.01662E-18	-0.22087051	-1.1866E-17	1	0
Environment(m)	0.283031592	-0.132067636	0.332738772	2.7047E-17	0	1

Chapter Six

Conclusion and Recommendation

6.1 Conclusion

The following points can be concluded from the present work.

1. Computational Modeling of Pipeline is a general method for predicting the performance of C.P.S and the best ICCP system design has been presented

2. Conductivity (resistivity) of the soil is playing two important roles in the design criteria of cathodic protection systems. The first role is occurring when placing the anode in a high conductivity environment; more uniform current and potential distribution will take place. In case of current distribution, the higher soil conductivity the higher current passing through the soil and as a consequence the lower in power consumption. Moreover, for the potential distribution, the lower in soil conductivity, the higher the potential needed to drive the current, and as a consequence the higher in power consumption. Second role is where the hydrogen evolution may occur in the surface of the cathode facing the anode due to the high value of the potential.

3. It is obvious that the anode at a distance of 33cm and depth of 35cm in moisted and dry soil is saving the maximum amount of power, due to the uniform distribution of current along the pipe, i.e. protection is achieved within the optimum values.

4. Coatings are the first line of defense in underground and submerged applications while coatings are the only defense in atmosphere application, the lowering of coating efficiency increasing the power outgoings on the cathodic protection emulate to the cost spent on coating.

6.2 Recommendation

1. In this study the internal resistance of the pipe was neglected during the calculations of the effect of soil conductivity. It is recommended to extend this study with consideration of this factor.

2. The methods presented would form the basis of a condition monitoring system or improved control system for cathodic protection systems.

3. Study and design of cathodic protection and the impact of types of soil

4. Study the effect of temperature on the performance of ICCP system.

5. Studying the influence of isothermal fluid flow on ICCP system and the effect of stray current on CPS.

References

1. http://events.nace.org/library/corrosion/Principles/Problem.asp, [U.S. GDP Gross Domestic Product Forecast]
2. [Kean and Davies, 2003] Kean, R. L. and Davies, K. G. (2003). www.npl.co.uk/ncs/docs/cathodic-protection.pdf.
3. Iraqi navigator interactive map,http://news.bbc.co.uk/2/shared/spl/hi/middle_east/02/iraq_key_maps/html/oil_fields.stm
4. Uhlig, H. H., "Corrosion and corrosion control", Johnwiely and Sons Inc, 2nd Edition, 1971
5. G. Prentice, Electrochemical Engineering Principles (Englewood Cliffs: PrenticeHall, 1991).
6. D. A. Jones, Principles and Prevention of Corrosion 2005
7. J. Bockris and D. Drazic, Electro-chemical Science (London: Taylor and Francis,1972).
8. J. Newman, Electrochemical Systems, 2nd edition (Englewood Cliffs: Prentice-Hall, 1991).
9. Roberge PR., “Handbook of Corrosion Engineering” .New York :McGraw -Hill,1 P,1999
10. Pravitasari, A., “Corrosion in Material of Construction”, The Norwegian University of Science and Technology, Trondheim, Norway :Springer, ISBN 1-85233-758-3,2003.www.majarimagazine.com.
11. Bardel, E., “Corrosion and Protection” ،Department of Machine Design and Materials Technology
12. Ginzel, R.K .& Kanters, W.A., “Pipeline Corrosion and Cracking and the Associated Calibration Considerations for Same Side Sizing

Applications:”Eclipse Scientific Products Inc., Williamsford, Ontario, Canada, VOL 7, NO .07, July 2002

13. AWWA, “Steel Water Pipe :A Guide for Design and Installation, Manual M11, 4th ed.”,American Water Works Association, Denver, CO ،.2004.
14. Lightenstein , Joram., “Fundamentals of Corrosion Causing and Mitigation”, Ebasco Service ,Incorporated ,Hosten,Texas ,1978
15. US Army of Corps of Engineers, “Painting :New Construction and Maintenance” Manual No .1110-2-3400, 30 April 1995.
16. Eugene D .Kale & Martin Sanders, “Presentation of Stray Current By The Maintenance -Of- Way,” Parsons Transportation Group, Inc .,2002.
17. Unified Facilites Criteria UFC “Operation and Maintenance : Cathodic Protection System”, January 2003 , Circular No .579, U.S .Government Printing Office, Washington,D.C., 1957.
18. Zaki Ahmad. Principles of Corrosion Engineering and Corrosion Control, 1st edition (2006).
19. Electrocorrosion and Protection of Metals: General approach with particular .By Joseph Riskin
20. PETRONAS Technical Standard, Design & Engineering Practice (CORE),Manual Cathodic Protection, PTS 30.10.73.
21. Klechka, E., Jr, P.E,”Corrosion protection for offshore pipelines”, Office of Special Programs and Continuing Education, 2004.
22. Glazov, N. P., Shamshetdinov, K. L. and Glazov, N. N., "Comparative analysis of requirement to insulating coating of pipelines", Protection of Metals, Vol.42, No.1, pp.94-99, 2006.
23. Corrosion Control: Engineering and Design By United States. Army. Corps of Engineers

24. Marshall E. Parker,Edward G. Peattie, Pipe Line Corrosion and Cathodic Protection,THIRD EDITION,1999
25. Robert Heidersbach, Metallurgy and Corrosion Control in Oil and Gas Production
26. Jin-Seok Oh* & Jong-Do Kim. KSME International Journal Vol, 18 No, 4. A new protection strategy of impressed current cathodic protection in ship (2004)
27. Shreir, L. L. and Jarman, R. A., ”Corrosion control”, 3rd Edition, Vol.2, 2000.
28. Handbook of Cathodic Corrosion Protection By Walter von Baeckmann, Wilhelm Schwenk, Werner Prinz
29. Cathodic Protection of Steel in Concrete and Masonry, Second Edition edited by Paul M. Chess, John P. Broomfield
30. Darowicki, K., ”Pro-ecological aspects of application of cathodic protection”, Journal of Environment Studies, Vol.10, No.5, pp.325-330, 2001.
31. Corrosion Prevention and Protection: Practical Solutions By Edward Ghali, Vedula S. Sastri, M. Elboujdaini
32. Peabody, A. W., "Control of pipeline corrosion’, ACE International the Corrosion Society, 2nd Edition, 2001.
33. R. G. Kasper, M. G. April, Corrosion 1983, 39, 181.
34. R. S. Munn, O. F. Devereux, Corrosion 1991, 47, 612.
35. M. E. Orazem, In: Cathodic Protection: Modeling and Experiment (Ed. M.E. Orazem) Research Topical Symposium, Corrosion/99, NACE international, Houston 1999.

36. "Mixed Potential Analysis of Sulfation of Molten Carbonate Fuel Cells," D. Townley, J. Winnick, and H. S. Huang, Journal of the Electrochemical Society, 127, 1104 (1980); discussion 127, 2653 (1980)
37. J. C. F. Telles, W. J. Mansur, L. C. Wrobel, M. G. Marinho, Corrosion 1990, 46, 513.
38. M. E. Orazem, J. M. Esteban, K. J. Kennelley, R. M. Degerstedt, Corrosion 1997, 53, 264.
39. Mohammed O. M. Al-Abdullatif, 2007, design and optimization of cathodic protection system used in prevention of pipeline corrosion,(Doctoral dissertation),King Saud University,Kingdom osSaudi Arabia.
40. Godwin Kakuba(2005),The Impressed Current Cathodic Protection System,(Master dissertation),Technische University Eindhoven.
41. Haider Mijed Abd AL-Rahman(2009),investigation of some parameters affecting of the cathodic protection of pipelines (Master dissertation),University of Basrah
42. Mohammed Hliyil Hafiz, 2006.modeling of pipeline corrosion controled by cathodic protection (Doctoral dissertation) University of Technology Baghdad,Iraq.
43. Kennethe. Jeffers,1999,electrical impedance spectroscopy for the characterrization of corrosion and cathodic protection of buried pipelines,(Master dissertation),University of Florida.
44. Agarwal, P., Moghissi, O. C., Orazem, M. E., and Garcia-Rubio, L. H. "Application of Measurement Models for Analysis of Impedance Spectra." Corrosion 49, 4 (1993): 278-289.

45. Durbha, M., Orazem, M. E., and Garcia-Rubio, L. H. “Spectroscopy Applications of the Kramers-Kronig Transforms: Implications for Error Structure Identification.”
46. Journal of the Electrochemical Society 144, 1 (1997): 48-55.
47. R. A. Adey, C. A. Brebbia and S. M. Niku, “Applications of Boundary Elements in Corrosion Engineering”, Boundary Elements VII, Villa Olmo, Lake Como, Italy. Computational Publications, 1985.
48. Wrobel, Luiz C., Miltiadous, Panayiotis. 2004. Genetic Algorithms for inverse Cathodic Protection Problems. Engineering analyses with boundary element, Vol. 28, Issue 3, 267- 277.
49. Adey, R. A. Niku, SN, 1985.A CAD system for the analysis and design of cathodic protection system. Plant Corrosion: prediction of Materials performance, Chapter 13, Institution of Corrosion Science and Technology, ELLIS HORWOOD LIMITED Publisher, Birmingham, UK.
50. Santana-Diaz, E., Adey, R. 2005 B .Predicting the coating condition on ships using ICCP system data. International Journal for Numerical Methods in Engineering, vol. 62, 727-746.
51. Yan, J.-F., Pakalapati, S.N. R., Nguyen, T. V., White R.E. and Griffin R.B.1992. Mathematical Modeling of cathodic Protection using the boundary element method with a non-linear polarization curve. The Journal Electrochemical Society, Vol.139, No.7, 1932- 1936.
52. Corrosion and Materials in the Oil and Gas Industries, by Reza Javaherdashti, Chikezie Nwaoha, Henry Tan,2013
53. Methodology and Technology for Power System Grounding, By Jinliang He, Rong Zeng, Bo Zhang,2012.

54. F. Brichau and J. Deconinck, “A Numerical Model for Cathodic Protection of Buried Pipe”, Corr. Sci., Vol. 50, No. 1 (1994) pp.39.
55. External Corrosion and Corrosion Control of Buried Water Mains, American Water Works Association, 2004
56. A. Benmoussat and M. Hadjel, “Corrosion Behavior of Low Carbon Line Pipe Steel in Soil Environment” The Journal of Corrosion Science and Engineering Vol. 7, No. 17, (January 2005).
57. R. Baboian, NACE Corrosion Engineer’s Reference Book, 3rd ed. NACE International, The Corrosion Society, 2002.
58. K. H. Logan, W. Rogers and J. F. Putman, “Pipeline Currents”,American Petroleum Institute, Bulletin 204, 116 (1930); Gas Age Record 64, 899 (1930).
59. Y. Joe et al, “Numerical Modeling of Cathodic Protection”, MRL Bull Res Div., Vol. No. 1, pp41-47, (March 1987).

APPENDIX A

EXPERIMENTAL DATA

Table (A-1) Experimental data of bare pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (20cm), Anode Depth (15cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.9	0.72	0.06	0.72	0.05	0.73	0.04	0.74	0.03	0.75	0.02	0.77	0.01
2	0.91	0.73	0.07	0.73	0.06	0.74	0.05	0.75	0.04	0.76	0.03	0.78	0.02
3	0.92	0.74	0.08	0.74	0.07	0.75	0.06	0.76	0.05	0.78	0.04	0.79	0.03
4	0.93	0.74	0.09	0.74	0.08	0.76	0.07	0.77	0.06	0.79	0.05	0.8	0.04
5	0.94	0.75	0.1	0.75	0.09	0.77	0.08	0.78	0.07	0.8	0.06	0.81	0.05
6	0.95	0.77	0.11	0.77	0.1	0.78	0.09	0.79	0.08	0.81	0.07	0.82	0.06
7	0.96	0.79	0.12	0.79	0.11	0.8	0.1	0.8	0.09	0.82	0.08	0.83	0.07
8	0.97	0.8	0.13	0.8	0.12	0.81	0.11	0.81	0.1	0.83	0.09	0.84	0.08
9	0.98	0.8	0.14	0.8	0.13	0.82	0.12	0.82	0.11	0.84	0.1	0.85	0.09
10	0.99	0.81	0.15	0.81	0.14	0.84	0.13	0.84	0.12	0.85	0.11	0.86	0.1
11	1	0.81	0.16	0.82	0.15	0.85	0.14	0.85	0.13	0.87	0.12	0.88	0.11
12	1.1	0.82	0.17	0.83	0.16	0.86	0.15	0.86	0.14	0.89	0.13	0.9	0.12
13	1.2	0.82	0.18	0.84	0.17	0.87	0.16	0.88	0.15	0.91	0.14	0.92	0.13
14	1.3	0.84	0.19	0.85	0.18	0.88	0.17	0.89	0.16	0.92	0.15	0.93	0.14

15	1.4	0.85	0.2	0.86	0.19	0.89	0.18	0.9	0.17	0.94	0.16	0.94	0.15
16	1.5	0.86	0.21	0.87	0.2	0.9	0.19	0.91	0.18	0.95	0.17	0.95	0.16
17	1.6	0.87	0.22	0.88	0.21	0.92	0.2	0.93	0.19	0.97	0.18	0.97	0.17
18	1.7	0.89	0.23	0.9	0.22	0.94	0.21	0.95	0.2	0.99	0.19	0.99	0.18
19	1.8	0.9	0.24	0.91	0.23	0.96	0.22	0.97	0.21	1.01	0.2	1.01	0.19
20	1.9	0.91	0.25	0.92	0.24	0.98	0.23	0.99	0.22	1.03	0.21	1.03	0.2
21	2.1	0.93	0.26	0.94	0.25	1.01	0.24	1.01	0.23	1.05	0.22	1.05	0.21
22	2.2	0.94	0.27	0.95	0.26	1.03	0.25	1.03	0.24	1.07	0.23	1.07	0.22
23	2.3	0.96	0.28	0.96	0.27	1.05	0.26	1.05	0.25	1.1	0.24	1.1	0.23
24	2.4	0.99	0.29	0.99	0.28	1.07	0.27	1.07	0.26	1.12	0.25	1.12	0.24
25	2.5	1.02	0.3	1.03	0.29	1.09	0.28	1.09	0.27	1.14	0.26	1.14	0.25
26	2.6	1.04	0.31	1.05	0.3	1.11	0.29	1.11	0.28	1.17	0.27	1.17	0.26
27	2.7	1.05	0.32	1.06	0.31	1.13	0.3	1.13	0.29	1.19	0.28	1.19	0.27
28	2.8	1.07	0.33	1.08	0.32	1.15	0.31	1.15	0.3	1.21	0.29	1.21	0.28
29	2.9	1.08	0.34	1.1	0.33	1.17	0.32	1.17	0.31	1.24	0.3	1.24	0.29
30	3	1.1	0.35	1.12	0.34	1.19	0.33	1.19	0.32	1.26	0.31	1.26	0.3
31	3.1	1.12	0.36	1.14	0.35	1.21	0.34	1.21	0.33	1.29	0.32	1.29	0.31
32	3.2	1.15	0.37	1.16	0.36	1.23	0.35	1.23	0.34	1.3	0.33	1.3	0.32
33	3.3	1.17	0.38	1.18	0.37	1.15	0.36	1.15	0.35	1.31	0.34	1.31	0.33
34	3.4	1.19	0.39	1.2	0.38	1.27	0.37	1.27	0.36	1.33	0.35	1.33	0.34

Table (A-2) Experimental data of bare pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (20cm), Anode Depth (35cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.95	0.77	0.1	0.77	0.08	0.78	0.06	0.8	0.04	0.81	0.02	0.81	0
2	0.96	0.78	0.11	0.78	0.09	0.79	0.07	0.8	0.05	0.82	0.03	0.83	0.01
3	0.97	0.79	0.12	0.79	0.1	0.8	0.08	0.81	0.06	0.83	0.04	0.84	0.02
4	0.98	0.8	0.13	0.8	0.11	0.81	0.09	0.82	0.07	0.84	0.05	0.85	0.03
5	0.99	0.81	0.14	0.81	0.12	0.82	0.1	0.83	0.08	0.85	0.06	0.86	0.04
6	1	0.82	0.15	0.82	0.13	0.83	0.11	0.84	0.09	0.86	0.07	0.88	0.05
7	1.1	0.83	0.16	0.83	0.14	0.84	0.12	0.85	0.1	0.87	0.08	0.88	0.06
8	1.2	0.83	0.17	0.84	0.15	0.85	0.13	0.86	0.11	0.88	0.09	0.89	0.07
9	1.3	0.84	0.18	0.85	0.16	0.86	0.14	0.87	0.12	0.89	0.1	0.89	0.08
10	1.4	0.84	0.19	0.86	0.17	0.87	0.15	0.88	0.13	0.9	0.11	0.9	0.09
11	1.5	0.85	0.2	0.87	0.18	0.88	0.16	0.89	0.14	0.91	0.12	0.92	0.1
12	1.6	0.87	0.21	0.88	0.19	0.89	0.17	0.9	0.15	0.92	0.13	0.93	0.11
13	1.7	0.88	0.22	0.89	0.2	0.9	0.18	0.91	0.16	0.93	0.14	0.95	0.12
1	0.95	0.77	0.1	0.77	0.08	0.78	0.06	0.8	0.04	0.81	0.02	0.81	0
2	0.96	0.78	0.11	0.78	0.09	0.79	0.07	0.8	0.05	0.82	0.03	0.83	0.01
3	0.97	0.79	0.12	0.79	0.1	0.8	0.08	0.81	0.06	0.83	0.04	0.84	0.02

14	1.8	0.89	0.23	0.9	0.21	0.91	0.19	0.93	0.17	0.95	0.15	0.97	0.13
15	1.9	0.9	0.24	0.91	0.22	0.91	0.2	0.94	0.18	0.97	0.16	0.99	0.14
16	2	0.91	0.25	0.92	0.23	0.92	0.21	0.95	0.19	0.99	0.17	1.01	0.15
17	2.1	0.92	0.26	0.93	0.24	0.93	0.22	0.96	0.2	1.02	0.18	1.03	0.16
18	2.2	0.93	0.27	0.94	0.25	0.94	0.23	0.97	0.21	1.03	0.19	1.04	0.17
19	2.3	0.94	0.28	0.95	0.26	0.95	0.24	0.98	0.22	1.04	0.2	1.06	0.18
20	2.4	0.95	0.29	0.96	0.27	0.96	0.25	0.99	0.23	1.06	0.21	1.08	0.19
21	2.5	0.96	0.3	0.97	0.28	0.97	0.26	1.01	0.24	1.08	0.22	1.1	0.2
22	2.6	0.97	0.31	0.98	0.29	0.98	0.27	1.03	0.25	1.1	0.23	1.11	0.21
23	2.7	0.99	0.32	0.99	0.3	1	0.28	1.04	0.26	1.11	0.24	1.13	0.22
24	2.8	1	0.33	1.02	0.31	1.02	0.29	1.05	0.27	1.12	0.25	1.15	0.23
25	2.9	1.02	0.34	1.03	0.32	1.03	0.3	1.06	0.28	1.14	0.26	1.17	0.24
26	3	1.03	0.35	1.04	0.33	1.04	0.31	1.07	0.29	1.16	0.27	1.19	0.25
27	3.1	1.04	0.36	1.05	0.34	1.05	0.32	1.08	0.3	1.17	0.28	1.2	0.26
28	3.2	1.05	0.37	1.06	0.35	1.06	0.33	1.09	0.31	1.18	0.29	1.23	0.27
29	3.3	1.06	0.38	1.07	0.36	1.08	0.34	1.11	0.32	1.19	0.3	1.25	0.28
30	3.4	1.07	0.39	1.08	0.37	1.09	0.35	1.12	0.33	1.21	0.31	1.26	0.29
31	3.5	1.08	0.4	1.09	0.38	1.1	0.36	1.14	0.34	1.22	0.32	1.27	0.3

32	3.6	1.09	0.41	1.1	0.39	1.12	0.37	1.16	0.35	1.23	0.33	1.29	0.31
33	3.7	1.1	0.42	1.11	0.4	1.13	0.38	1.17	0.36	1.25	0.34	1.3	0.32
34	3.8	1.11	0.43	1.12	0.41	1.14	0.39	1.18	0.37	1.26	0.35	1.32	0.33
36	4	1.14	0.45	1.14	0.43	1.16	0.41	1.2	0.39	1.28	0.37	1.36	0.35
37	4.1	1.15	0.46	1.16	0.44	1.18	0.42	1.21	0.4	1.3	0.38	1.37	0.36
38	4.2	1.16	0.47	1.17	0.45	1.2	0.43	1.22	0.41	1.32	0.39	1.39	0.37
39	4.3	1.17	0.48	1.18	0.46	1.18	0.44	1.23	0.42	1.35	0.4	1.41	0.38
40	4.4	1.19	0.49	1.19	0.47	1.21	0.45	1.25	0.43	1.37	0.41	1.42	0.39
41	4.5	1.2	0.5	1.21	0.48	1.22	0.46	1.26	0.44	1.38	0.42	1.43	0.4
42	4.6	1.22	0.51	1.22	0.49	1.23	0.47	1.27	0.45	1.4	0.43	1.44	0.41
43	4.7	1.23	0.52	1.24	0.5	1.24	0.48	1.28	0.46	1.41	0.44	1.45	0.42

Table (A-3) Experimental data of bare pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (33cm), Anode Depth (15cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.95	0.76	0.08	0.76	0.06	0.77	0.04	0.79	0.02	0.8	0	0.81	0
2	0.96	0.77	0.09	0.77	0.07	0.78	0.05	0.8	0.03	0.81	0.01	0.82	0
3	0.97	0.78	0.1	0.78	0.08	0.79	0.06	0.81	0.04	0.82	0.02	0.83	0.01
4	0.98	0.79	0.11	0.79	0.09	0.8	0.07	0.82	0.05	0.83	0.03	0.84	0.02
5	0.99	0.8	0.12	0.8	0.1	0.81	0.08	0.83	0.06	0.84	0.04	0.85	0.03
6	1	0.8	0.13	0.81	0.11	0.82	0.09	0.84	0.07	0.85	0.05	0.86	0.04
7	1.1	0.82	0.14	0.82	0.12	0.84	0.1	0.85	0.08	0.86	0.06	0.87	0.05
8	1.2	0.83	0.15	0.83	0.13	0.85	0.11	0.86	0.09	0.87	0.07	0.88	0.06
9	1.3	0.84	0.16	0.84	0.14	0.86	0.12	0.87	0.1	0.88	0.08	0.89	0.07
10	1.4	0.84	0.17	0.85	0.15	0.87	0.13	0.88	0.11	0.89	0.09	0.9	0.08
11	1.5	0.85	0.18	0.86	0.16	0.89	0.14	0.89	0.12	0.9	0.1	0.91	0.09
12	1.6	0.88	0.19	0.88	0.17	0.9	0.15	0.9	0.13	0.91	0.11	0.92	0.1
13	1.7	0.89	0.2	0.89	0.18	0.91	0.16	0.91	0.14	0.92	0.12	0.93	0.11
14	1.8	0.9	0.21	0.9	0.19	0.92	0.17	0.93	0.15	0.94	0.13	0.95	0.12
15	1.9	0.91	0.22	0.91	0.2	0.93	0.18	0.94	0.16	0.95	0.14	0.96	0.13
16	2	0.92	0.23	0.92	0.21	0.94	0.19	0.95	0.17	0.96	0.15	0.97	0.14

17	2.1	0.93	0.24	0.93	0.22	0.95	0.2	0.96	0.18	0.97	0.16	0.98	0.15
18	2.2	0.94	0.25	0.94	0.23	0.96	0.21	0.97	0.19	0.98	0.17	0.99	0.16
19	2.3	0.95	0.26	0.95	0.24	0.97	0.22	0.98	0.2	0.99	0.18	1	0.17
20	2.4	0.96	0.27	0.96	0.25	0.98	0.23	0.99	0.21	1	0.19	1.01	0.18
21	2.5	0.98	0.28	0.98	0.26	0.99	0.24	1	0.22	1.02	0.2	1.02	0.19
22	2.6	0.99	0.29	0.99	0.27	1.01	0.25	1.02	0.23	1.03	0.21	1.03	0.2
23	2.7	1	0.3	1	0.28	1.02	0.26	1.03	0.24	1.04	0.22	1.04	0.21
24	2.8	1.02	0.31	1.02	0.29	1.03	0.27	1.04	0.25	1.06	0.23	1.06	0.22
25	2.9	1.03	0.32	1.03	0.3	1.05	0.28	1.06	0.26	1.07	0.24	1.07	0.23
26	3	1.05	0.33	1.05	0.31	1.07	0.29	1.07	0.27	1.08	0.25	1.08	0.24
27	3.1	1.06	0.34	1.06	0.32	1.08	0.3	1.08	0.28	1.1	0.26	1.1	0.25
28	3.2	1.07	0.35	1.07	0.33	1.1	0.31	1.1	0.29	1.12	0.27	1.12	0.26
29	3.3	1.09	0.36	1.09	0.34	1.12	0.32	1.12	0.3	1.13	0.28	1.13	0.27
30	3.4	1.1	0.37	1.1	0.35	1.13	0.33	1.13	0.31	1.15	0.29	1.15	0.28
31	3.5	1.12	0.38	1.12	0.36	1.14	0.34	1.14	0.32	1.16	0.3	1.16	0.29
32	3.6	1.13	0.39	1.13	0.37	1.15	0.35	1.15	0.33	1.17	0.31	1.17	0.3
33	3.7	1.15	0.4	1.15	0.38	1.17	0.36	1.17	0.34	1.19	0.32	1.19	0.31
34	3.8	1.16	0.41	1.16	0.39	1.18	0.37	1.18	0.35	1.2	0.33	1.2	0.32
35	3.9	1.17	0.42	1.17	0.4	1.19	0.38	1.19	0.36	1.21	0.34	1.21	0.33
36	4	1.18	0.43	1.18	0.41	1.2	0.39	1.2	0.37	1.22	0.35	1.22	0.34
37	4.1	1.19	0.44	1.19	0.42	1.21	0.4	1.21	0.38	1.23	0.36	1.23	0.35
38	4.2	1.2	0.45	1.2	0.43	1.22	0.41	1.22	0.39	1.24	0.37	1.25	0.36

Table (A-4) Experimental data of bare pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (33cm), Anode Depth (35cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.98	0.74	0.1	0.75	0.08	0.76	0.06	0.77	0.04	0.78	0.02	0.79	0
2	0.99	0.75	0.11	0.76	0.09	0.77	0.07	0.78	0.05	0.79	0.03	0.81	0.01
3	1	0.76	0.12	0.77	0.1	0.78	0.08	0.79	0.06	0.81	0.04	0.82	0.02
4	1.1	0.77	0.13	0.78	0.11	0.79	0.09	0.81	0.07	0.82	0.05	0.83	0.03
5	1.2	0.78	0.14	0.79	0.12	0.81	0.1	0.82	0.08	0.83	0.06	0.84	0.04
6	1.3	0.79	0.15	0.81	0.13	0.82	0.11	0.83	0.09	0.84	0.07	0.86	0.05
7	1.4	0.81	0.16	0.82	0.14	0.83	0.12	0.84	0.1	0.86	0.08	0.85	0.06
8	1.5	0.82	0.17	0.83	0.15	0.84	0.13	0.86	0.11	0.85	0.09	0.87	0.07
9	1.6	0.83	0.18	0.84	0.16	0.86	0.14	0.85	0.12	0.87	0.1	0.89	0.08
10	1.7	0.84	0.19	0.86	0.17	0.85	0.15	0.87	0.13	0.89	0.11	0.9	0.09
11	1.8	0.85	0.2	0.85	0.18	0.87	0.16	0.89	0.14	0.9	0.12	0.91	0.1
12	1.9	0.86	0.21	0.87	0.19	0.89	0.17	0.9	0.15	0.91	0.13	0.92	0.11
13	2	0.87	0.22	0.89	0.2	0.9	0.18	0.91	0.16	0.92	0.14	0.93	0.12
14	2.1	0.89	0.23	0.9	0.21	0.91	0.19	0.92	0.17	0.93	0.15	0.95	0.13
15	2.2	0.9	0.24	0.91	0.22	0.92	0.2	0.93	0.18	0.95	0.16	0.96	0.14
16	2.3	0.91	0.25	0.92	0.23	0.93	0.21	0.95	0.19	0.96	0.17	0.97	0.15

17	2.4	0.92	0.26	0.93	0.24	0.95	0.22	0.96	0.2	0.97	0.18	0.98	0.16
18	2.5	0.93	0.27	0.95	0.25	0.96	0.23	0.97	0.21	0.98	0.19	0.99	0.17
19	2.6	0.95	0.28	0.96	0.26	0.97	0.24	0.98	0.22	0.99	0.2	1	0.18
20	2.7	0.96	0.29	0.97	0.27	0.98	0.25	0.99	0.23	1	0.21	1.02	0.19
21	2.8	0.97	0.3	0.98	0.28	0.99	0.26	1	0.24	1.02	0.22	1.03	0.2
22	0.98	0.74	0.1	0.75	0.08	0.76	0.06	0.77	0.04	0.78	0.02	0.79	0
23	0.99	0.75	0.11	0.76	0.09	0.77	0.07	0.78	0.05	0.79	0.03	0.81	0.01
24	1	0.76	0.12	0.77	0.1	0.78	0.08	0.79	0.06	0.81	0.04	0.82	0.02
25	2.9	0.98	0.31	0.99	0.29	1	0.27	1.02	0.25	1.03	0.23	1.05	0.21
26	3	0.99	0.32	1	0.3	1.02	0.28	1.03	0.26	1.05	0.24	1.07	0.22
27	3.1	1	0.33	1.02	0.31	1.03	0.29	1.05	0.27	1.07	0.25	1.08	0.23
28	3.2	1.02	0.34	1.03	0.32	1.05	0.3	1.07	0.28	1.08	0.26	1.1	0.24
29	3.3	1.03	0.35	1.05	0.33	1.07	0.31	1.08	0.29	1.1	0.27	1.12	0.25
30	3.4	1.05	0.36	1.07	0.34	1.08	0.32	1.1	0.3	1.12	0.28	1.13	0.26
31	3.5	1.07	0.37	1.08	0.35	1.1	0.33	1.12	0.31	1.13	0.29	1.14	0.27
32	3.6	1.08	0.38	1.1	0.36	1.12	0.34	1.13	0.32	1.14	0.3	1.15	0.28
33	3.7	1.1	0.39	1.12	0.37	1.13	0.35	1.14	0.33	1.15	0.31	1.16	0.29
34	3.8	1.12	0.4	1.13	0.38	1.14	0.36	1.15	0.34	1.16	0.32	1.18	0.3
35	3.9	1.13	0.41	1.14	0.39	1.15	0.37	1.16	0.35	1.18	0.33	1.19	0.31
36	4	1.14	0.42	1.15	0.4	1.16	0.38	1.18	0.36	1.19	0.34	1.2	0.32
37	4.1	1.15	0.43	1.16	0.41	1.18	0.39	1.19	0.37	1.2	0.35	1.21	0.33
38	4.2	1.16	0.44	1.18	0.42	1.19	0.4	1.2	0.38	1.21	0.36	1.22	0.34

39	3.4	1.18	0.45	1.19	0.43	1.2	0.41	1.21	0.39	1.22	0.37	1.23	0.35
40	3.5	1.19	0.46	1.2	0.44	1.21	0.42	1.22	0.4	1.23	0.38	1.24	0.36
41	3.6	1.2	0.47	1.21	0.45	1.22	0.43	1.23	0.41	1.24	0.39	1.25	0.37
42	3.7	1.21	0.48	1.22	0.46	1.23	0.44	1.24	0.42	1.25	0.4	1.26	0.38

Table (A-5) Experimental data of bare pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (50cm), Anode Depth (15cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.95	0.71	0.06	0.72	0.04	0.73	0.02	0.74	0	0.76	0	0.77	0
2	0.96	0.72	0.07	0.73	0.05	0.74	0.03	0.75	0.01	0.77	0	0.78	0
3	0.97	0.72	0.08	0.74	0.06	0.75	0.04	0.76	0.02	0.78	0	0.79	0
4	0.98	0.73	0.09	0.74	0.07	0.76	0.05	0.78	0.03	0.79	0.01	0.8	0
5	0.99	0.74	0.1	0.75	0.08	0.77	0.06	0.79	0.04	0.8	0.02	0.82	0
6	1	0.75	0.11	0.76	0.09	0.78	0.07	0.8	0.05	0.81	0.03	0.84	0.01
7	1.1	0.76	0.12	0.77	0.1	0.79	0.08	0.81	0.06	0.82	0.04	0.85	0.02
8	1.2	0.77	0.13	0.78	0.11	0.8	0.09	0.82	0.07	0.83	0.05	0.86	0.03
9	1.3	0.78	0.14	0.78	0.12	0.81	0.1	0.83	0.08	0.84	0.06	0.88	0.04
10	1.4	0.79	0.15	0.79	0.13	0.82	0.11	0.84	0.09	0.86	0.07	0.89	0.05
11	1.5	0.8	0.16	0.8	0.14	0.83	0.12	0.85	0.1	0.87	0.08	0.91	0.06
12	1.6	0.81	0.17	0.81	0.15	0.84	0.13	0.85	0.11	0.88	0.09	0.92	0.07
13	1.7	0.83	0.18	0.82	0.16	0.85	0.14	0.86	0.12	0.9	0.1	0.94	0.08
14	1.8	0.84	0.19	0.83	0.17	0.86	0.15	0.87	0.13	0.91	0.11	0.96	0.09
15	1.9	0.85	0.2	0.84	0.18	0.87	0.16	0.88	0.14	0.92	0.12	0.97	0.1
16	2	0.86	0.21	0.85	0.19	0.88	0.17	0.89	0.15	0.93	0.13	0.99	0.11

17	2.1	0.87	0.22	0.86	0.2	0.9	0.18	0.91	0.16	0.95	0.14	1	0.12
18	2.2	0.88	0.23	0.87	0.21	0.91	0.19	0.91	0.17	0.97	0.15	1.02	0.13
19	2.3	0.89	0.24	0.88	0.22	0.92	0.2	0.92	0.18	0.99	0.16	1.04	0.14
20	2.4	0.89	0.25	0.88	0.23	0.94	0.21	0.94	0.19	1	0.17	1.06	0.15
21	2.5	0.9	0.26	0.89	0.24	0.95	0.22	0.95	0.2	1.03	0.18	1.08	0.16
22	2.6	0.91	0.27	0.9	0.25	0.96	0.23	0.96	0.21	1.04	0.19	1.1	0.17
23	2.7	0.92	0.28	0.91	0.26	0.97	0.24	0.98	0.22	1.06	0.2	1.12	0.18
24	2.8	0.93	0.29	0.92	0.27	0.98	0.25	0.99	0.23	1.08	0.21	1.14	0.19
25	2.9	0.93	0.3	0.93	0.28	0.9	0.26	1	0.24	1.09	0.22	1.16	0.2
26	3	0.94	0.31	0.94	0.29	1.01	0.27	1.01	0.25	1.11	0.23	1.18	0.21
27	3.1	0.95	0.32	0.95	0.3	1.02	0.28	1.02	0.26	1.12	0.24	1.2	0.22
28	3.2	0.96	0.33	0.96	0.31	1.04	0.29	1.04	0.27	1.14	0.25	1.22	0.23
29	3.3	0.97	0.34	0.97	0.32	1.05	0.3	1.05	0.28	1.16	0.26	1.23	0.24
30	3.4	0.98	0.35	0.98	0.33	1.06	0.31	1.06	0.29	1.18	0.27	1.26	0.25
31	3.5	1	0.36	1	0.34	1.07	0.32	1.07	0.3	1.2	0.28	1.27	0.26
32	3.6	1.01	0.37	1.01	0.35	1.08	0.33	1.09	0.31	1.22	0.29	1.29	0.27
33	3.7	1.02	0.38	1.02	0.36	1.09	0.34	1.1	0.32	1.25	0.3	1.31	0.28
34	3.8	1.03	0.39	1.03	0.37	1.1	0.35	1.11	0.33	1.26	0.31	1.33	0.29
35	3.9	1.04	0.4	1.04	0.38	1.12	0.36	1.12	0.34	1.27	0.32	1.34	0.3
36	4	1.05	0.41	1.05	0.39	1.13	0.37	1.13	0.35	1.29	0.33	1.36	0.31

Table (A-6) Experimental data of bare pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (50cm), Anode Depth (35cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.98	0.72	0.08	0.72	0.06	0.74	0.04	0.75	0.02	0.77	0	0.78	0
2	0.99	0.73	0.09	0.73	0.07	0.75	0.05	0.76	0.03	0.78	0.01	0.79	0
3	1	0.74	0.1	0.74	0.08	0.76	0.06	0.78	0.04	0.79	0.02	0.8	0
4	1.1	0.75	0.11	0.75	0.09	0.76	0.07	0.79	0.05	0.8	0.03	0.81	0.01
5	1.2	0.76	0.12	0.77	0.1	0.78	0.08	0.8	0.06	0.81	0.04	0.82	0.02
6	1.3	0.77	0.13	0.78	0.11	0.79	0.09	0.81	0.07	0.82	0.05	0.83	0.03
7	1.4	0.78	0.14	0.79	0.12	0.81	0.1	0.82	0.08	0.83	0.06	0.84	0.04
8	1.5	0.79	0.15	0.81	0.13	0.82	0.11	0.83	0.09	0.84	0.07	0.85	0.05
9	1.6	0.81	0.16	0.82	0.14	0.83	0.12	0.84	0.1	0.85	0.08	0.86	0.06
10	1.7	0.82	0.17	0.83	0.15	0.84	0.13	0.85	0.11	0.87	0.09	0.87	0.07
11	1.8	0.83	0.18	0.84	0.16	0.86	0.14	0.87	0.12	0.88	0.1	0.88	0.08
12	1.9	0.84	0.19	0.86	0.17	0.85	0.15	0.88	0.13	0.89	0.11	0.89	0.09
13	2	0.85	0.2	0.85	0.18	0.87	0.16	0.89	0.14	0.9	0.12	1	0.1
14	2.1	0.86	0.21	0.87	0.19	0.89	0.17	0.9	0.15	1	0.13	1.01	0.11
15	2.2	0.87	0.22	0.89	0.2	0.9	0.18	1	0.16	1.02	0.14	1.02	0.12
16	2.3	0.89	0.23	0.9	0.21	0.91	0.19	1.02	0.17	1.04	0.15	1.04	0.13

17	2.4	0.9	0.24	0.91	0.22	0.92	0.2	1.04	0.18	1.05	0.16	1.06	0.14
18	2.5	0.91	0.25	0.92	0.23	0.93	0.21	1.05	0.19	1.06	0.17	1.08	0.15
19	2.6	0.92	0.26	0.93	0.24	0.95	0.22	1.06	0.2	1.08	0.18	1.1	0.16
20	2.7	0.93	0.27	0.95	0.25	0.96	0.23	1.08	0.21	1.1	0.19	1.12	0.17
21	2.8	0.95	0.28	0.96	0.26	0.97	0.24	1.1	0.22	1.11	0.2	1.14	0.18
22	2.9	0.96	0.29	0.97	0.27	0.98	0.25	1.11	0.23	1.13	0.21	1.16	0.19
23	3	0.97	0.3	0.98	0.28	0.99	0.26	1.13	0.24	1.16	0.22	1.18	0.2
24	3.1	0.98	0.31	0.99	0.29	1	0.27	1.16	0.25	1.18	0.23	1.2	0.21
25	3.2	0.99	0.32	1	0.3	1.02	0.28	1.18	0.26	1.2	0.24	1.22	0.22
26	3.3	1	0.33	1.02	0.31	1.03	0.29	1.2	0.27	1.22	0.25	1.25	0.23
27	3.4	1.02	0.34	1.03	0.32	1.05	0.3	1.22	0.28	1.25	0.26	1.26	0.24
28	3.5	1.03	0.35	1.05	0.33	1.07	0.31	1.25	0.29	1.26	0.27	1.27	0.25
29	3.6	1.05	0.36	1.07	0.34	1.08	0.32	1.26	0.3	1.27	0.28	1.29	0.26
30	3.7	1.07	0.37	1.08	0.35	1.1	0.33	1.27	0.31	1.29	0.29	1.31	0.27
31	3.8	1.08	0.38	1.1	0.36	1.12	0.34	1.29	0.32	1.31	0.3	1.33	0.28
32	3.9	1.1	0.39	1.12	0.37	1.13	0.35	1.31	0.33	1.33	0.31	1.35	0.29
33	4	1.12	0.4	1.13	0.38	1.14	0.36	1.33	0.34	1.35	0.32	1.37	0.3
34	4.1	1.13	0.41	1.14	0.39	1.15	0.37	1.35	0.35	1.37	0.33	1.39	0.31
35	4.2	1.14	0.42	1.15	0.4	1.16	0.38	1.37	0.36	1.39	0.34	1.41	0.32
36	3.4	1.15	0.43	1.16	0.41	1.18	0.39	1.39	0.37	1.41	0.35	1.43	0.33

37	3.5	1.16	0.44	1.18	0.42	1.19	0.4	1.41	0.38	1.43	0.36	1.45	0.34
38	3.6	1.18	0.45	1.19	0.43	1.2	0.41	1.43	0.39	1.45	0.37	1.47	0.35
39	3.7	1.19	0.46	1.2	0.44	1.15	0.42	1.45	0.4	1.47	0.38	1.49	0.36
40	3.5	1.2	0.47	1.15	0.45	1.16	0.43	1.47	0.41	1.49	0.39	1.5	0.37
41	3.6	1.15	0.48	1.16	0.46	1.17	0.44	1.49	0.42	1.5	0.4	1.55	0.38
42	3.7	1.16	0.4	1.17	0.47	1.18	0.45	1.5	0.43	1.55	0.41	1.58	0.39
43	3.8	1.17	0.4	1.18	0.48	1.19	0.46	1.55	0.44	1.58	0.42	1.6	0.4
44	3.9	1.18	0.4	1.19	0.4	1.21	0.47	1.58	0.45	1.6	0.43	1.61	0.41
45	4	1.19	0.4	1.21	0.4	1.22	0.48	1.6	0.46	1.61	0.44	1.62	0.42
46	4.1	1.21	0.4	1.22	0.4	1.24	0.4	1.61	0.47	1.62	0.45	1.63	0.43
47	4.2	1.22	0.4	1.24	0.4	1.25	0.4	1.62	0.48	1.63	0.46	1.65	0.44
48	4.3	1.24	0.5	1.25	0.4	1.27	0.4	1.63	0.4	1.65	0.47	1.66	0.45

APPENDIX B

EXPERIMENTAL DATA

Table (B-1) Experimental data of bare pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (20cm), Anode Depth (15cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.9	0.72	0.06	0.72	0.05	0.73	0.04	0.74	0.03	0.75	0.02	0.77	0.01
2	0.91	0.73	0.07	0.73	0.06	0.74	0.05	0.75	0.04	0.76	0.03	0.78	0.02
3	0.92	0.74	0.08	0.74	0.07	0.75	0.06	0.76	0.05	0.78	0.04	0.79	0.03
4	0.93	0.74	0.09	0.74	0.08	0.76	0.07	0.77	0.06	0.79	0.05	0.8	0.04
5	0.94	0.75	0.1	0.75	0.09	0.77	0.08	0.78	0.07	0.8	0.06	0.81	0.05
6	0.95	0.77	0.11	0.77	0.1	0.78	0.09	0.79	0.08	0.81	0.07	0.82	0.06
7	0.96	0.79	0.12	0.79	0.11	0.8	0.1	0.8	0.09	0.82	0.08	0.83	0.07
8	0.97	0.8	0.13	0.8	0.12	0.81	0.11	0.81	0.1	0.83	0.09	0.84	0.08
9	0.98	0.8	0.14	0.8	0.13	0.82	0.12	0.82	0.11	0.84	0.1	0.85	0.09
10	0.99	0.81	0.15	0.81	0.14	0.84	0.13	0.84	0.12	0.85	0.11	0.86	0.1
11	1	0.81	0.16	0.82	0.15	0.85	0.14	0.85	0.13	0.87	0.12	0.88	0.11
12	1.1	0.82	0.17	0.83	0.16	0.86	0.15	0.86	0.14	0.89	0.13	0.9	0.12
13	1.2	0.82	0.18	0.84	0.17	0.87	0.16	0.88	0.15	0.91	0.14	0.92	0.13
14	1.3	0.84	0.19	0.85	0.18	0.88	0.17	0.89	0.16	0.92	0.15	0.93	0.14

15	1.4	0.85	0.2	0.86	0.19	0.89	0.18	0.9	0.17	0.94	0.16	0.94	0.15
16	1.5	0.86	0.21	0.87	0.2	0.9	0.19	0.91	0.18	0.95	0.17	0.95	0.16
17	1.6	0.87	0.22	0.88	0.21	0.92	0.2	0.93	0.19	0.97	0.18	0.97	0.17
18	1.7	0.89	0.23	0.9	0.22	0.94	0.21	0.95	0.2	0.99	0.19	0.99	0.18
19	1.8	0.9	0.24	0.91	0.23	0.96	0.22	0.97	0.21	1.01	0.2	1.01	0.19
20	1.9	0.91	0.25	0.92	0.24	0.98	0.23	0.99	0.22	1.03	0.21	1.03	0.2
21	2.1	0.93	0.26	0.94	0.25	1.01	0.24	1.01	0.23	1.05	0.22	1.05	0.21
22	2.2	0.94	0.27	0.95	0.26	1.03	0.25	1.03	0.24	1.07	0.23	1.07	0.22
23	2.3	0.96	0.28	0.96	0.27	1.05	0.26	1.05	0.25	1.1	0.24	1.1	0.23
25	2.5	1.02	0.3	1.03	0.29	1.09	0.28	1.09	0.27	1.14	0.26	1.14	0.25
26	2.6	1.04	0.31	1.05	0.3	1.11	0.29	1.11	0.28	1.17	0.27	1.17	0.26
27	2.7	1.05	0.32	1.06	0.31	1.13	0.3	1.13	0.29	1.19	0.28	1.19	0.27
28	2.8	1.07	0.33	1.08	0.32	1.15	0.31	1.15	0.3	1.21	0.29	1.21	0.28
29	2.9	1.08	0.34	1.1	0.33	1.17	0.32	1.17	0.31	1.24	0.3	1.24	0.29
30	3	1.1	0.35	1.12	0.34	1.19	0.33	1.19	0.32	1.26	0.31	1.26	0.3
31	3.1	1.12	0.36	1.14	0.35	1.21	0.34	1.21	0.33	1.29	0.32	1.29	0.31
32	3.2	1.15	0.37	1.16	0.36	1.23	0.35	1.23	0.34	1.3	0.33	1.3	0.32
33	3.3	1.17	0.38	1.18	0.37	1.15	0.36	1.15	0.35	1.31	0.34	1.31	0.33
34	3.4	1.19	0.39	1.2	0.38	1.27	0.37	1.27	0.36	1.33	0.35	1.33	0.34
35	3.5	1.2	0.4	1.22	0.39	1.29	0.38	1.29	0.37	1.34	0.36	1.34	0.35
36	3.6	1.21	0.41	1.23	0.4	1.3	0.39	1.3	0.38	1.36	0.37	1.36	0.36

Table (B-2) Experimental data of bare pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (20cm), Anode Depth (35cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.95	0.77	0.1	0.77	0.08	0.78	0.06	0.8	0.04	0.81	0.02	0.81	0
2	0.96	0.78	0.11	0.78	0.09	0.79	0.07	0.8	0.05	0.82	0.03	0.83	0.01
3	0.97	0.79	0.12	0.79	0.1	0.8	0.08	0.81	0.06	0.83	0.04	0.84	0.02
4	0.98	0.8	0.13	0.8	0.11	0.81	0.09	0.82	0.07	0.84	0.05	0.85	0.03
5	0.99	0.81	0.14	0.81	0.12	0.82	0.1	0.83	0.08	0.85	0.06	0.86	0.04
6	1	0.82	0.15	0.82	0.13	0.83	0.11	0.84	0.09	0.86	0.07	0.88	0.05
7	1.1	0.83	0.16	0.83	0.14	0.84	0.12	0.85	0.1	0.87	0.08	0.88	0.06
8	1.2	0.83	0.17	0.84	0.15	0.85	0.13	0.86	0.11	0.88	0.09	0.89	0.07
9	1.3	0.84	0.18	0.85	0.16	0.86	0.14	0.87	0.12	0.89	0.1	0.89	0.08
10	1.4	0.84	0.19	0.86	0.17	0.87	0.15	0.88	0.13	0.9	0.11	0.9	0.09
11	1.5	0.85	0.2	0.87	0.18	0.88	0.16	0.89	0.14	0.91	0.12	0.92	0.1
12	1.6	0.87	0.21	0.88	0.19	0.89	0.17	0.9	0.15	0.92	0.13	0.93	0.11
13	1.7	0.88	0.22	0.89	0.2	0.9	0.18	0.91	0.16	0.93	0.14	0.95	0.12
14	1.8	0.89	0.23	0.9	0.21	0.91	0.19	0.93	0.17	0.95	0.15	0.97	0.13
15	1.9	0.9	0.24	0.91	0.22	0.91	0.2	0.94	0.18	0.97	0.16	0.99	0.14
16	2	0.91	0.25	0.92	0.23	0.92	0.21	0.95	0.19	0.99	0.17	1.01	0.15
17	2.1	0.92	0.26	0.93	0.24	0.93	0.22	0.96	0.2	1.02	0.18	1.03	0.16

18	2.2	0.93	0.27	0.94	0.25	0.94	0.23	0.97	0.21	1.03	0.19	1.04	0.17
19	2.3	0.94	0.28	0.95	0.26	0.95	0.24	0.98	0.22	1.04	0.2	1.06	0.18
20	2.4	0.95	0.29	0.96	0.27	0.96	0.25	0.99	0.23	1.06	0.21	1.08	0.19
21	2.5	0.96	0.3	0.97	0.28	0.97	0.26	1.01	0.24	1.08	0.22	1.1	0.2
22	2.6	0.97	0.31	0.98	0.29	0.98	0.27	1.03	0.25	1.1	0.23	1.11	0.21
23	2.7	0.99	0.32	0.99	0.3	1	0.28	1.04	0.26	1.11	0.24	1.13	0.22
24	2.8	1	0.33	1.02	0.31	1.02	0.29	1.05	0.27	1.12	0.25	1.15	0.23
25	2.9	1.02	0.34	1.03	0.32	1.03	0.3	1.06	0.28	1.14	0.26	1.17	0.24
26	3	1.03	0.35	1.04	0.33	1.04	0.31	1.07	0.29	1.16	0.27	1.19	0.25
27	3.1	1.04	0.36	1.05	0.34	1.05	0.32	1.08	0.3	1.17	0.28	1.2	0.26
28	3.2	1.05	0.37	1.06	0.35	1.06	0.33	1.09	0.31	1.18	0.29	1.23	0.27
29	3.3	1.06	0.38	1.07	0.36	1.08	0.34	1.11	0.32	1.19	0.3	1.25	0.28
30	3.4	1.07	0.39	1.08	0.37	1.09	0.35	1.12	0.33	1.21	0.31	1.26	0.29
31	3.5	1.08	0.4	1.09	0.38	1.1	0.36	1.14	0.34	1.22	0.32	1.27	0.3
32	3.6	1.09	0.41	1.1	0.39	1.12	0.37	1.16	0.35	1.23	0.33	1.29	0.31
33	3.7	1.1	0.42	1.11	0.4	1.13	0.38	1.17	0.36	1.25	0.34	1.3	0.32
34	3.8	1.11	0.43	1.12	0.41	1.14	0.39	1.18	0.37	1.26	0.35	1.32	0.33
35	3.9	1.13	0.44	1.13	0.42	1.15	0.4	1.19	0.38	1.27	0.36	1.34	0.34
36	4	1.14	0.45	1.14	0.43	1.16	0.41	1.2	0.39	1.28	0.37	1.36	0.35
37	4.1	1.15	0.46	1.16	0.44	1.18	0.42	1.21	0.4	1.3	0.38	1.37	0.36
38	4.2	1.16	0.47	1.17	0.45	1.2	0.43	1.22	0.41	1.32	0.39	1.39	0.37
39	4.3	1.17	0.48	1.18	0.46	1.18	0.44	1.23	0.42	1.35	0.4	1.41	0.38
40	4.4	1.19	0.49	1.19	0.47	1.21	0.45	1.25	0.43	1.37	0.41	1.42	0.39

Table (B-3) Experimental data of bare pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (33cm), Anode Depth (15cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.95	0.76	0.08	0.76	0.06	0.77	0.04	0.79	0.02	0.8	0	0.81	0
2	0.96	0.77	0.09	0.77	0.07	0.78	0.05	0.8	0.03	0.81	0.01	0.82	0
3	0.97	0.78	0.1	0.78	0.08	0.79	0.06	0.81	0.04	0.82	0.02	0.83	0.01
4	0.98	0.79	0.11	0.79	0.09	0.8	0.07	0.82	0.05	0.83	0.03	0.84	0.02
5	0.99	0.8	0.12	0.8	0.1	0.81	0.08	0.83	0.06	0.84	0.04	0.85	0.03
6	1	0.8	0.13	0.81	0.11	0.82	0.09	0.84	0.07	0.85	0.05	0.86	0.04
7	1.1	0.82	0.14	0.82	0.12	0.84	0.1	0.85	0.08	0.86	0.06	0.87	0.05
8	1.2	0.83	0.15	0.83	0.13	0.85	0.11	0.86	0.09	0.87	0.07	0.88	0.06
9	1.3	0.84	0.16	0.84	0.14	0.86	0.12	0.87	0.1	0.88	0.08	0.89	0.07
10	1.4	0.84	0.17	0.85	0.15	0.87	0.13	0.88	0.11	0.89	0.09	0.9	0.08
11	1.5	0.85	0.18	0.86	0.16	0.89	0.14	0.89	0.12	0.9	0.1	0.91	0.09
12	1.6	0.88	0.19	0.88	0.17	0.9	0.15	0.9	0.13	0.91	0.11	0.92	0.1
13	1.7	0.89	0.2	0.89	0.18	0.91	0.16	0.91	0.14	0.92	0.12	0.93	0.11
14	1.8	0.9	0.21	0.9	0.19	0.92	0.17	0.93	0.15	0.94	0.13	0.95	0.12
15	1.9	0.91	0.22	0.91	0.2	0.93	0.18	0.94	0.16	0.95	0.14	0.96	0.13
16	2	0.92	0.23	0.92	0.21	0.94	0.19	0.95	0.17	0.96	0.15	0.97	0.14
17	2.1	0.93	0.24	0.93	0.22	0.95	0.2	0.96	0.18	0.97	0.16	0.98	0.15
18	2.2	0.94	0.25	0.94	0.23	0.96	0.21	0.97	0.19	0.98	0.17	0.99	0.16

19	2.3	0.95	0.26	0.95	0.24	0.97	0.22	0.98	0.2	0.99	0.18	1	0.17
20	2.4	0.96	0.27	0.96	0.25	0.98	0.23	0.99	0.21	1	0.19	1.01	0.18
21	2.5	0.98	0.28	0.98	0.26	0.99	0.24	1	0.22	1.02	0.2	1.02	0.19
22	2.6	0.99	0.29	0.99	0.27	1.01	0.25	1.02	0.23	1.03	0.21	1.03	0.2
23	2.7	1	0.3	1	0.28	1.02	0.26	1.03	0.24	1.04	0.22	1.04	0.21
24	2.8	1.02	0.31	1.02	0.29	1.03	0.27	1.04	0.25	1.06	0.23	1.06	0.22
25	2.9	1.03	0.32	1.03	0.3	1.05	0.28	1.06	0.26	1.07	0.24	1.07	0.23
26	3	1.05	0.33	1.05	0.31	1.07	0.29	1.07	0.27	1.08	0.25	1.08	0.24
27	3.1	1.06	0.34	1.06	0.32	1.08	0.3	1.08	0.28	1.1	0.26	1.1	0.25
28	3.2	1.07	0.35	1.07	0.33	1.1	0.31	1.1	0.29	1.12	0.27	1.12	0.26
29	3.3	1.09	0.36	1.09	0.34	1.12	0.32	1.12	0.3	1.13	0.28	1.13	0.27
30	3.4	1.1	0.37	1.1	0.35	1.13	0.33	1.13	0.31	1.15	0.29	1.15	0.28
31	3.5	1.12	0.38	1.12	0.36	1.14	0.34	1.14	0.32	1.16	0.3	1.16	0.29
32	3.6	1.13	0.39	1.13	0.37	1.15	0.35	1.15	0.33	1.17	0.31	1.17	0.3
33	3.7	1.15	0.4	1.15	0.38	1.17	0.36	1.17	0.34	1.19	0.32	1.19	0.31
34	3.8	1.16	0.41	1.16	0.39	1.18	0.37	1.18	0.35	1.2	0.33	1.2	0.32
35	3.9	1.17	0.42	1.17	0.4	1.19	0.38	1.19	0.36	1.21	0.34	1.21	0.33
36	4	1.18	0.43	1.18	0.41	1.2	0.39	1.2	0.37	1.22	0.35	1.22	0.34
37	4.1	1.19	0.44	1.19	0.42	1.21	0.4	1.21	0.38	1.23	0.36	1.23	0.35
38	4.2	1.2	0.45	1.2	0.43	1.22	0.41	1.22	0.39	1.24	0.37	1.25	0.36

Table (B-4) Experimental data of bare pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (33cm), Anode Depth (35cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.98	0.74	0.1	0.75	0.08	0.76	0.06	0.77	0.04	0.78	0.02	0.79	0
2	0.99	0.75	0.11	0.76	0.09	0.77	0.07	0.78	0.05	0.79	0.03	0.81	0.01
3	1	0.76	0.12	0.77	0.1	0.78	0.08	0.79	0.06	0.81	0.04	0.82	0.02
4	1.1	0.77	0.13	0.78	0.11	0.79	0.09	0.81	0.07	0.82	0.05	0.83	0.03
5	1.2	0.78	0.14	0.79	0.12	0.81	0.1	0.82	0.08	0.83	0.06	0.84	0.04
6	1.3	0.79	0.15	0.81	0.13	0.82	0.11	0.83	0.09	0.84	0.07	0.86	0.05
7	1.4	0.81	0.16	0.82	0.14	0.83	0.12	0.84	0.1	0.86	0.08	0.85	0.06
8	1.5	0.82	0.17	0.83	0.15	0.84	0.13	0.86	0.11	0.85	0.09	0.87	0.07
9	1.6	0.83	0.18	0.84	0.16	0.86	0.14	0.85	0.12	0.87	0.1	0.89	0.08
10	1.7	0.84	0.19	0.86	0.17	0.85	0.15	0.87	0.13	0.89	0.11	0.9	0.09
11	1.8	0.85	0.2	0.85	0.18	0.87	0.16	0.89	0.14	0.9	0.12	0.91	0.1
12	1.9	0.86	0.21	0.87	0.19	0.89	0.17	0.9	0.15	0.91	0.13	0.92	0.11
13	2	0.87	0.22	0.89	0.2	0.9	0.18	0.91	0.16	0.92	0.14	0.93	0.12
14	2.1	0.89	0.23	0.9	0.21	0.91	0.19	0.92	0.17	0.93	0.15	0.95	0.13
15	2.2	0.9	0.24	0.91	0.22	0.92	0.2	0.93	0.18	0.95	0.16	0.96	0.14
16	2.3	0.91	0.25	0.92	0.23	0.93	0.21	0.95	0.19	0.96	0.17	0.97	0.15
17	2.4	0.92	0.26	0.93	0.24	0.95	0.22	0.96	0.2	0.97	0.18	0.98	0.16

18	2.5	0.93	0.27	0.95	0.25	0.96	0.23	0.97	0.21	0.98	0.19	0.99	0.17
19	2.6	0.95	0.28	0.96	0.26	0.97	0.24	0.98	0.22	0.99	0.2	1	0.18
20	2.7	0.96	0.29	0.97	0.27	0.98	0.25	0.99	0.23	1	0.21	1.02	0.19
21	2.8	0.97	0.3	0.98	0.28	0.99	0.26	1	0.24	1.02	0.22	1.03	0.2
22	2.9	0.98	0.31	0.99	0.29	1	0.27	1.02	0.25	1.03	0.23	1.05	0.21
23	3	0.99	0.32	1	0.3	1.02	0.28	1.03	0.26	1.05	0.24	1.07	0.22
24	3.1	1	0.33	1.02	0.31	1.03	0.29	1.05	0.27	1.07	0.25	1.08	0.23
25	3.2	1.02	0.34	1.03	0.32	1.05	0.3	1.07	0.28	1.08	0.26	1.1	0.24
26	3.3	1.03	0.35	1.05	0.33	1.07	0.31	1.08	0.29	1.1	0.27	1.12	0.25
27	3.4	1.05	0.36	1.07	0.34	1.08	0.32	1.1	0.3	1.12	0.28	1.13	0.26
28	3.5	1.07	0.37	1.08	0.35	1.1	0.33	1.12	0.31	1.13	0.29	1.14	0.27
29	3.6	1.08	0.38	1.1	0.36	1.12	0.34	1.13	0.32	1.14	0.3	1.15	0.28
30	3.7	1.1	0.39	1.12	0.37	1.13	0.35	1.14	0.33	1.15	0.31	1.16	0.29
31	3.8	1.12	0.4	1.13	0.38	1.14	0.36	1.15	0.34	1.16	0.32	1.18	0.3
32	3.9	1.13	0.41	1.14	0.39	1.15	0.37	1.16	0.35	1.18	0.33	1.19	0.31
33	4	1.14	0.42	1.15	0.4	1.16	0.38	1.18	0.36	1.19	0.34	1.2	0.32
34	4.1	1.15	0.43	1.16	0.41	1.18	0.39	1.19	0.37	1.2	0.35	1.21	0.33
35	4.2	1.16	0.44	1.18	0.42	1.19	0.4	1.2	0.38	1.21	0.36	1.22	0.34
36	3.4	1.18	0.45	1.19	0.43	1.2	0.41	1.21	0.39	1.22	0.37	1.23	0.35
37	3.5	1.19	0.46	1.2	0.44	1.21	0.42	1.22	0.4	1.23	0.38	1.24	0.36
38	3.6	1.2	0.47	1.21	0.45	1.22	0.43	1.23	0.41	1.24	0.39	1.25	0.37
39	3.7	1.21	0.48	1.22	0.46	1.23	0.44	1.24	0.42	1.25	0.4	1.26	0.38

Table (B-5) Experimental data of bare pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (50cm), Anode Depth (15cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.95	0.71	0.06	0.72	0.04	0.73	0.02	0.74	0	0.76	0	0.77	0
2	0.96	0.72	0.07	0.73	0.05	0.74	0.03	0.75	0.01	0.77	0	0.78	0
3	0.97	0.72	0.08	0.74	0.06	0.75	0.04	0.76	0.02	0.78	0	0.79	0
4	0.98	0.73	0.09	0.74	0.07	0.76	0.05	0.78	0.03	0.79	0.01	0.8	0
5	0.99	0.74	0.1	0.75	0.08	0.77	0.06	0.79	0.04	0.8	0.02	0.82	0
6	1	0.75	0.11	0.76	0.09	0.78	0.07	0.8	0.05	0.81	0.03	0.84	0.01
7	1.1	0.76	0.12	0.77	0.1	0.79	0.08	0.81	0.06	0.82	0.04	0.85	0.02
8	1.2	0.77	0.13	0.78	0.11	0.8	0.09	0.82	0.07	0.83	0.05	0.86	0.03
9	1.3	0.78	0.14	0.78	0.12	0.81	0.1	0.83	0.08	0.84	0.06	0.88	0.04
10	1.4	0.79	0.15	0.79	0.13	0.82	0.11	0.84	0.09	0.86	0.07	0.89	0.05
11	1.5	0.8	0.16	0.8	0.14	0.83	0.12	0.85	0.1	0.87	0.08	0.91	0.06
12	1.6	0.81	0.17	0.81	0.15	0.84	0.13	0.85	0.11	0.88	0.09	0.92	0.07
13	1.7	0.83	0.18	0.82	0.16	0.85	0.14	0.86	0.12	0.9	0.1	0.94	0.08
14	1.8	0.84	0.19	0.83	0.17	0.86	0.15	0.87	0.13	0.91	0.11	0.96	0.09
15	1.9	0.85	0.2	0.84	0.18	0.87	0.16	0.88	0.14	0.92	0.12	0.97	0.1
16	2	0.86	0.21	0.85	0.19	0.88	0.17	0.89	0.15	0.93	0.13	0.99	0.11
17	2.1	0.87	0.22	0.86	0.2	0.9	0.18	0.91	0.16	0.95	0.14	1	0.12

18	2.2	0.88	0.23	0.87	0.21	0.91	0.19	0.91	0.17	0.97	0.15	1.02	0.13
19	2.3	0.89	0.24	0.88	0.22	0.92	0.2	0.92	0.18	0.99	0.16	1.04	0.14
20	2.4	0.89	0.25	0.88	0.23	0.94	0.21	0.94	0.19	1	0.17	1.06	0.15
21	2.5	0.9	0.26	0.89	0.24	0.95	0.22	0.95	0.2	1.03	0.18	1.08	0.16
22	2.6	0.91	0.27	0.9	0.25	0.96	0.23	0.96	0.21	1.04	0.19	1.1	0.17
23	2.7	0.92	0.28	0.91	0.26	0.97	0.24	0.98	0.22	1.06	0.2	1.12	0.18
24	2.8	0.93	0.29	0.92	0.27	0.98	0.25	0.99	0.23	1.08	0.21	1.14	0.19
25	2.9	0.93	0.3	0.93	0.28	0.9	0.26	1	0.24	1.09	0.22	1.16	0.2
26	3	0.94	0.31	0.94	0.29	1.01	0.27	1.01	0.25	1.11	0.23	1.18	0.21
27	3.1	0.95	0.32	0.95	0.3	1.02	0.28	1.02	0.26	1.12	0.24	1.2	0.22
28	3.2	0.96	0.33	0.96	0.31	1.04	0.29	1.04	0.27	1.14	0.25	1.22	0.23
29	3.3	0.97	0.34	0.97	0.32	1.05	0.3	1.05	0.28	1.16	0.26	1.23	0.24
30	3.4	0.98	0.35	0.98	0.33	1.06	0.31	1.06	0.29	1.18	0.27	1.26	0.25
31	3.5	1	0.36	1	0.34	1.07	0.32	1.07	0.3	1.2	0.28	1.27	0.26
32	3.6	1.01	0.37	1.01	0.35	1.08	0.33	1.09	0.31	1.22	0.29	1.29	0.27
33	3.7	1.02	0.38	1.02	0.36	1.09	0.34	1.1	0.32	1.25	0.3	1.31	0.28
34	3.8	1.03	0.39	1.03	0.37	1.1	0.35	1.11	0.33	1.26	0.31	1.33	0.29
35	3.9	1.04	0.4	1.04	0.38	1.12	0.36	1.12	0.34	1.27	0.32	1.34	0.3
36	4	1.05	0.41	1.05	0.39	1.13	0.37	1.13	0.35	1.29	0.33	1.36	0.31
37	4.1	1.06	0.42	1.06	0.4	1.14	0.38	1.14	0.36	1.3	0.34	1.38	0.32
38	4.2	1.07	0.43	1.07	0.41	1.16	0.39	1.16	0.37	1.32	0.35	1.4	0.33
39	3.4	1.08	0.44	1.08	0.42	1.17	0.4	1.17	0.38	1.35	0.36	1.42	0.34

40	*3.5*	*1.09*	*0.45*	*1.09*	*0.43*	*1.18*	*0.41*	*1.18*	*0.39*	*1.36*	*0.37*	*1.43*	*0.35*
41	*3.6*	*1.1*	*0.46*	*1.1*	*0.44*	*1.19*	*0.42*	*1.19*	*0.4*	*1.38*	*0.38*	*1.45*	*0.36*
42	*3.7*	*1.11*	*0.47*	*1.11*	*0.45*	*1.2*	*0.43*	*1.21*	*0.41*	*1.39*	*0.39*	*1.47*	*0.37*
43	*3.8*	*1.12*	*0.48*	*1.12*	*0.46*	*1.22*	*0.44*	*1.22*	*0.42*	*1.4*	*0.4*	*1.48*	*0.38*
44	*3.9*	*1.13*	*0.49*	*1.13*	*0.47*	*1.23*	*0.45*	*1.23*	*0.43*	*1.41*	*0.41*	*1.5*	*0.39*
45	*4*	*1.14*	*0.5*	*1.14*	*0.48*	*1.24*	*0.46*	*1.24*	*0.44*	*1.43*	*0.42*	*1.51*	*0.4*
46	*4.1*	*1.15*	*0.51*	*1.15*	*0.49*	*1.25*	*0.47*	*1.25*	*0.45*	*1.45*	*0.43*	*1.53*	*0.41*
47	*4.2*	*1.17*	*0.52*	*1.17*	*0.5*	*1.26*	*0.48*	*1.27*	*0.46*	*1.47*	*0.44*	*1.55*	*0.42*
48	*4.3*	*1.18*	*0.53*	*1.18*	*0.51*	*1.27*	*0.49*	*1.28*	*0.47*	*1.48*	*0.45*	*1.57*	*0.43*

Table (B-6) Experimental data of bare pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (50cm), Anode Depth (35cm).

		Position of the reference electrode along the pipe length											
		0cm		10cm		20cm		30cm		40cm		50cm	
NO	Voltage applied(V)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)	Potential(V)	Current(mA)
1	0.98	0.72	0.08	0.72	0.06	0.74	0.04	0.75	0.02	0.77	0	0.78	0
2	0.99	0.73	0.09	0.73	0.07	0.75	0.05	0.76	0.03	0.78	0.01	0.79	0
3	1	0.74	0.1	0.74	0.08	0.76	0.06	0.78	0.04	0.79	0.02	0.8	0
4	1.1	0.75	0.11	0.75	0.09	0.76	0.07	0.79	0.05	0.8	0.03	0.81	0.01
5	1.2	0.76	0.12	0.77	0.1	0.78	0.08	0.8	0.06	0.81	0.04	0.82	0.02
6	1.3	0.77	0.13	0.78	0.11	0.79	0.09	0.81	0.07	0.82	0.05	0.83	0.03
7	1.4	0.78	0.14	0.79	0.12	0.81	0.1	0.82	0.08	0.83	0.06	0.84	0.04
8	1.5	0.79	0.15	0.81	0.13	0.82	0.11	0.83	0.09	0.84	0.07	0.85	0.05
9	1.6	0.81	0.16	0.82	0.14	0.83	0.12	0.84	0.1	0.85	0.08	0.86	0.06
10	1.7	0.82	0.17	0.83	0.15	0.84	0.13	0.85	0.11	0.87	0.09	0.87	0.07
11	1.8	0.83	0.18	0.84	0.16	0.86	0.14	0.87	0.12	0.88	0.1	0.88	0.08
12	1.9	0.84	0.19	0.86	0.17	0.85	0.15	0.88	0.13	0.89	0.11	0.89	0.09
13	2	0.85	0.2	0.85	0.18	0.87	0.16	0.89	0.14	0.9	0.12	1	0.1
14	2.1	0.86	0.21	0.87	0.19	0.89	0.17	0.9	0.15	1	0.13	1.01	0.11
15	2.2	0.87	0.22	0.89	0.2	0.9	0.18	1	0.16	1.02	0.14	1.02	0.12
16	2.3	0.89	0.23	0.9	0.21	0.91	0.19	1.02	0.17	1.04	0.15	1.04	0.13

17	2.4	0.9	0.24	0.91	0.22	0.92	0.2	1.04	0.18	1.05	0.16	1.06	0.14
18	2.5	0.91	0.25	0.92	0.23	0.93	0.21	1.05	0.19	1.06	0.17	1.08	0.15
19	2.6	0.92	0.26	0.93	0.24	0.95	0.22	1.06	0.2	1.08	0.18	1.1	0.16
20	2.7	0.93	0.27	0.95	0.25	0.96	0.23	1.08	0.21	1.1	0.19	1.12	0.17
21	2.8	0.95	0.28	0.96	0.26	0.97	0.24	1.1	0.22	1.11	0.2	1.14	0.18
22	2.9	0.96	0.29	0.97	0.27	0.98	0.25	1.11	0.23	1.13	0.21	1.16	0.19
23	3	0.97	0.3	0.98	0.28	0.99	0.26	1.13	0.24	1.16	0.22	1.18	0.2
24	3.1	0.98	0.31	0.99	0.29	1	0.27	1.16	0.25	1.18	0.23	1.2	0.21
25	3.2	0.99	0.32	1	0.3	1.02	0.28	1.18	0.26	1.2	0.24	1.22	0.22
26	3.3	1	0.33	1.02	0.31	1.03	0.29	1.2	0.27	1.22	0.25	1.25	0.23
27	3.4	1.02	0.34	1.03	0.32	1.05	0.3	1.22	0.28	1.25	0.26	1.26	0.24
28	3.5	1.03	0.35	1.05	0.33	1.07	0.31	1.25	0.29	1.26	0.27	1.27	0.25
29	3.6	1.05	0.36	1.07	0.34	1.08	0.32	1.26	0.3	1.27	0.28	1.29	0.26
30	3.7	1.07	0.37	1.08	0.35	1.1	0.33	1.27	0.31	1.29	0.29	1.31	0.27
31	3.8	1.08	0.38	1.1	0.36	1.12	0.34	1.29	0.32	1.31	0.3	1.33	0.28
32	3.9	1.1	0.39	1.12	0.37	1.13	0.35	1.31	0.33	1.33	0.31	1.35	0.29
33	4	1.12	0.4	1.13	0.38	1.14	0.36	1.33	0.34	1.35	0.32	1.37	0.3
34	4.1	1.13	0.41	1.14	0.39	1.15	0.37	1.35	0.35	1.37	0.33	1.39	0.31
35	4.2	1.14	0.42	1.15	0.4	1.16	0.38	1.37	0.36	1.39	0.34	1.41	0.32
36	3.4	1.15	0.43	1.16	0.41	1.18	0.39	1.39	0.37	1.41	0.35	1.43	0.33

37	3.5	1.16	0.44	1.18	0.42	1.19	0.4	1.41	0.38	1.43	0.36	1.45	0.34
38	3.6	1.18	0.45	1.19	0.43	1.2	0.41	1.43	0.39	1.45	0.37	1.47	0.35
39	3.7	1.19	0.46	1.2	0.44	1.15	0.42	1.45	0.4	1.47	0.38	1.49	0.36
40	3.5	1.2	0.47	1.15	0.45	1.16	0.43	1.47	0.41	1.49	0.39	1.5	0.37
41	3.6	1.15	0.48	1.16	0.46	1.17	0.44	1.49	0.42	1.5	0.4	1.55	0.38
42	3.7	1.16	0.4	1.17	0.47	1.18	0.45	1.5	0.43	1.55	0.41	1.58	0.39
43	3.8	1.17	0.4	1.18	0.48	1.19	0.46	1.55	0.44	1.58	0.42	1.6	0.4
44	3.9	1.18	0.4	1.19	0.4	1.21	0.47	1.58	0.45	1.6	0.43	1.61	0.41
45	4	1.19	0.4	1.21	0.4	1.22	0.48	1.6	0.46	1.61	0.44	1.62	0.42
46	4.1	1.21	0.4	1.22	0.4	1.24	0.4	1.61	0.47	1.62	0.45	1.63	0.43
47	4.2	1.22	0.4	1.24	0.4	1.25	0.4	1.62	0.48	1.63	0.46	1.65	0.44
48	4.3	1.24	0.5	1.25	0.4	1.27	0.4	1.63	0.4	1.65	0.47	1.66	0.45

APPENDIX C

EXPERIMENTAL DATA

Table (C-1) Experimental data of coated pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (20cm), Anode Depth (15cm).

NO	Voltage applied (V)	Potential (V)	Current (mA)
1	0	0.6	0
2	0.1	0.65	0
3	0.2	0.7	0
4	0.3	0.75	0
5	0.4	0.8	0
6	0.5	0.85	0.01
7	0.6	0.91	0.02
8	0.7	0.96	0.03
9	0.8	1.01	0.04
10	0.9	1.07	0.05
11	1	1.12	0.06

Table (C-2) Experimental data of coated pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (20cm), Anode Depth (35cm).

NO	Voltage applied (V)	Potential (V)	Current (mA)
1	0	0.59	0
2	0.1	0.64	0
3	0.2	0.69	0
4	0.3	0.74	0
5	0.4	0.8	0
6	0.5	0.85	0.01
7	0.6	0.9	0.01
8	0.7	0.95	0.02
9	0.8	1	0.03
10	0.9	1.06	0.04
11	1	1.11	0.05

Table (C-3) Experimental data of coated pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (33cm), Anode Depth (15cm).

NO	Voltage applied (V)	Potential (V)	Current (mA)
1	0	0.58	0
2	0.1	0.64	0
3	0.2	0.69	0
4	0.3	0.74	0
5	0.4	0.79	0.01
6	0.5	0.84	0.02
7	0.6	0.89	0.03
8	0.7	0.94	0.04
9	0.8	1	0.05
10	0.9	1.05	0.06
11	1	1.1	0.07

Table (C-4) Experimental data of coated pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (33cm), Anode Depth (35cm).

NO	Voltage applied (V)	Potential (V)	Current (mA)
1	0	0.57	0
2	0.1	0.63	0
3	0.2	0.68	0
4	0.3	0.73	0
5	0.4	0.79	0
6	0.5	0.84	0.01
7	0.6	0.89	0.02
8	0.7	0.94	0.03
9	0.8	0.99	0.04
10	0.9	1.04	0.05
11	1	1.09	0.06

Table (C-5) Experimental data of coated pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (50cm), Anode Depth (15cm).

NO	Voltage applied (V)	Potential (V)	Current (mA)
1	0	0.56	0
2	0.1	0.61	0
3	0.2	0.67	0
4	0.3	0.72	0.01
5	0.4	0.78	0.02
6	0.5	0.84	0.03
7	0.6	0.89	0.04
8	0.7	0.94	0.05
9	0.8	0.99	0.06
10	0.9	1.05	0.07
11	1	1.1	0.08

Table (C-6) Experimental data of coated pipe with dry environment, resistivity of (1500 Ω. Cm), Anode Distance (50cm), Anode Depth (35cm).

NO	Voltage applied (V)	Potential (V)	Current (mA)
1	0	0.55	0
2	0.1	0.61	0
3	0.2	0.67	0
4	0.3	0.73	0
5	0.4	0.78	0.01
6	0.5	0.83	0.02
7	0.6	0.89	0.03
8	0.7	0.94	0.04
9	0.8	1	0.05
10	0.9	1.05	0.06
11	1	1.08	0.07

APPENDIX D

EXPERIMENTAL DATA

Table (D-1) Experimental data of coated pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (20cm), Anode Depth (15cm).

NO	Voltage applied (V)	Potential(V)	Current (mA)
1	0	0.66	0
2	0.1	0.7	0
3	0.2	0.75	0
4	0.3	0.8	0.01
5	0.4	0.85	0.02
6	0.5	0.91	0.03
7	0.6	1	0.04
8	0.7	1.05	0.05
9	0.8	1.1	0.06
10	0.9	1.15	0.07
11	1	1.22	0.08

Table (D-2) Experimental data of coated pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (20cm), Anode Depth (35cm).

NO	Voltage applied (V)	Potential(V)	Current (mA)
1	0	0.65	0
2	0.1	0.7	0
3	0.2	0.75	0
4	0.3	0.8	0
5	0.4	0.86	0.01
6	0.5	0.93	0.02
7	0.6	1.01	0.03
8	0.7	1.09	0.04
9	0.8	1.14	0.05
10	0.9	1.19	0.06
11	1	1.22	0.07

Table (D-3) Experimental data of coated pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (33cm), Anode Depth (15cm).

NO	Voltage applied (V)	Potential(V)	Current (mA)
1	0	0.64	0
2	0.1	0.69	0
3	0.2	0.74	0.01
4	0.3	0.8	0.02
5	0.4	0.85	0.03
6	0.5	0.9	0.04
7	0.6	0.96	0.05
8	0.7	1.02	0.06
9	0.8	1.1	0.07
10	0.9	1.14	0.08
11	1	1.21	0.09

Table (D-4) Experimental data of coated pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (33cm), Anode Depth (35cm).

NO	Voltage applied (V)	Potential(V)	Current (mA)
1	0	0.63	0
2	0.1	0.68	0
3	0.2	0.74	0
4	0.3	0.79	0.01
5	0.4	0.84	0.02
6	0.5	0.89	0.03
7	0.6	0.98	0.04
8	0.7	1.03	0.05
9	0.8	1.09	0.06
10	0.9	1.14	0.07
11	1	1.2	0.08

Table (D-5) Experimental data of coated pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (50cm), Anode Depth (15cm).

NO	Voltage applied (V)	Potential(V)	Current (mA)
1	0	0.62	0
2	0.1	0.68	0.01
3	0.2	0.73	0.02
4	0.3	0.79	0.03
5	0.4	0.84	0.04
6	0.5	0.9	0.05
7	0.6	0.96	0.06
8	0.7	1.02	0.07
9	0.8	1.11	0.08
10	0.9	1.18	0.09
11	1	1.2	0.1

Table (D-6) Experimental data of coated pipe with moisture environment, resistivity of (750 Ω. Cm), Anode Distance (50cm), Anode Depth (35cm).

NO	Voltage applied (V)	Potential(V)	Current (mA)
1	0	0.61	0
2	0.1	0.66	0
3	0.2	0.72	0.01
4	0.3	0.78	0.02
5	0.4	0.84	0.03
6	0.5	0.91	0.04
7	0.6	1	0.05
8	0.7	1.05	0.06
9	0.8	1.11	0.07
10	0.9	1.16	0.08
11	1	1.2	0.09

الخلاصة

نمذجه للحماية الكاثودية لخطوط الأنابيب

ان تآكل الهياكل المعدنية المدفونة في التربة والتي على اتصال مع التربة لفترة طويلة تعتبر مشكلة هندسية واقتصادية كبيرة.

في جميع انحاء العالم هنالك الكثير من انابيب النفط والغاز والماء وكابلات الاتصالات وكذلك صهاريج التخزين والمباني والاسسات والعديد من الهياكل الاخرى مدفونة في التربة. والتي تعاني بدورها من مشاكل التآكل التي تؤثر بشكل رئيسي على الاسطح الخارجية لهذة الهياكل وبالتالي تلفها.

في العديد من بلدان العالم تعتبر خطوط الانابيب من اهم وسائل نقل المواد الهيدروكربونية, وهذا ينطبق على نقل النفط الخام والمنتجات المستخلصة والغاز الطبيعي. والتآكل مشكلة شائعة لهذه الهياكل والمعادن المدفونة في التربة. والنظرة العالمية المهتمة بهذا الموضوع يمكن ملاحظتها من خلال كمية الابحاث والدراسات التي اجريت في هذا المجال . محاولات عديدة قد اجريت للتغلب على هذة المشكلة عن طريق استخدام طرق او تقنيات متعددة, والاكثر شيوعاً وتطبيقا هي تقنيه الحماية الكاثودية.

في هذا البحث تم استخدام انبوب الصلب الكاربوني بطول (100 cm) مغمور في صندوق خشبي يحتوي على التربة, وتم تطبيق الحماية الكاثودية بطريقة التيار المسلط, بأستخدام مجهز طاقة ودائرة كهربائية مغلقة وتمت دراسة عدة عوامل مهمة تؤثر على حماية الانبوب من التاكل, مثل موقع الانود (بُعد و عمق), مقاومة التربة (رطبة, جافة) ظروف الانبوب (مغلق غير مغلق), توزيع الجهد الكهربائية و التيار على طول الانبوب (الكاثود) وكمية التيار الكهربائي اللازم للحصول على الحماية الكاثودية.

علاقة قد تحققت لمحاكاة مدايات من العوامل المؤثرة على الحماية الكاثودية بواسطة التيار المسلط. الانحدار من هذا النموذج للبيانات والنتائج المحصلة تنتج عنها نتائج معلمة تختلف اعتماداً على تاثير العامل نفسهُ.

معادلتين قد تحققت للانابيب المغلفة والغير المغلفة توضح تأثير عدة عوامل للحصول على فرق جهد الحماية الكاثودية (850-) ملي فولت وعلاقة كل عامل مع الاخر.

انبوب صلب كاربوني غير مغلف

$$\xi = 0.791+0.091\,V +0.144\,I -0.00188\,D -0.00180\,Dp -0.00537\,m$$

انبوب صلب كاربوني مغلف

$$\xi = 0.467+0.742\,V -1.675\,I +0.00057\,D -0.00067\,Dp +0.2299\,m$$

شكر وتقدير

الحمد لله الذي انعم علينا بتمام الصحة والعافية وفضلنا بنعمة العقل وزيننا بتاج العلم والصلاة والسلام على اشرف الخلق محمد وعلى اله وصحبه اجمعين.

اقف عاجزا على التعبير عن مدى الشكر والامتنان الذي اود ان ابديه الى مشرفي الفاضل ورئيس قسم الهندسة الكيمياوية الاستاذ المساعد الدكتور نصير عبود عيسى الحبوبي لما بذله من جهد وعناء لاخراج هذا الناتج العلمي بهذه الحله الغراء.

واتقدم بالشكر الاجلال الى والدي الكريمين اللذان حفوني بالدموع والدعاء كما واشكر السيد عائد مدلول أحمد لما قدمه لي من مساعدة معنويه وعلمية.

وشكري الجزيل لجميع زملائي الذين لم يقصرو في مساعدتي واخص منهم السيد هجار أزاد أحمد مديري في العمل لما قدمه لي من تسهيلات لاجراء بعض التجارب العملية.

أنس ثائر علي

أداء الحماية الكاثودية لخطوط الانابيب

رسالة
مقدمة الى كلية الهندسة في جامعة النهرين

وهي جزء من متطلبات نيل درجة ماجستير علوم

في الهندسة الكيمياوية

من قبل

أنس ثائر علي

بكالوريوس علوم في الهندسة الكيمياويه 2006

رمضان 1435

حزيران 2014